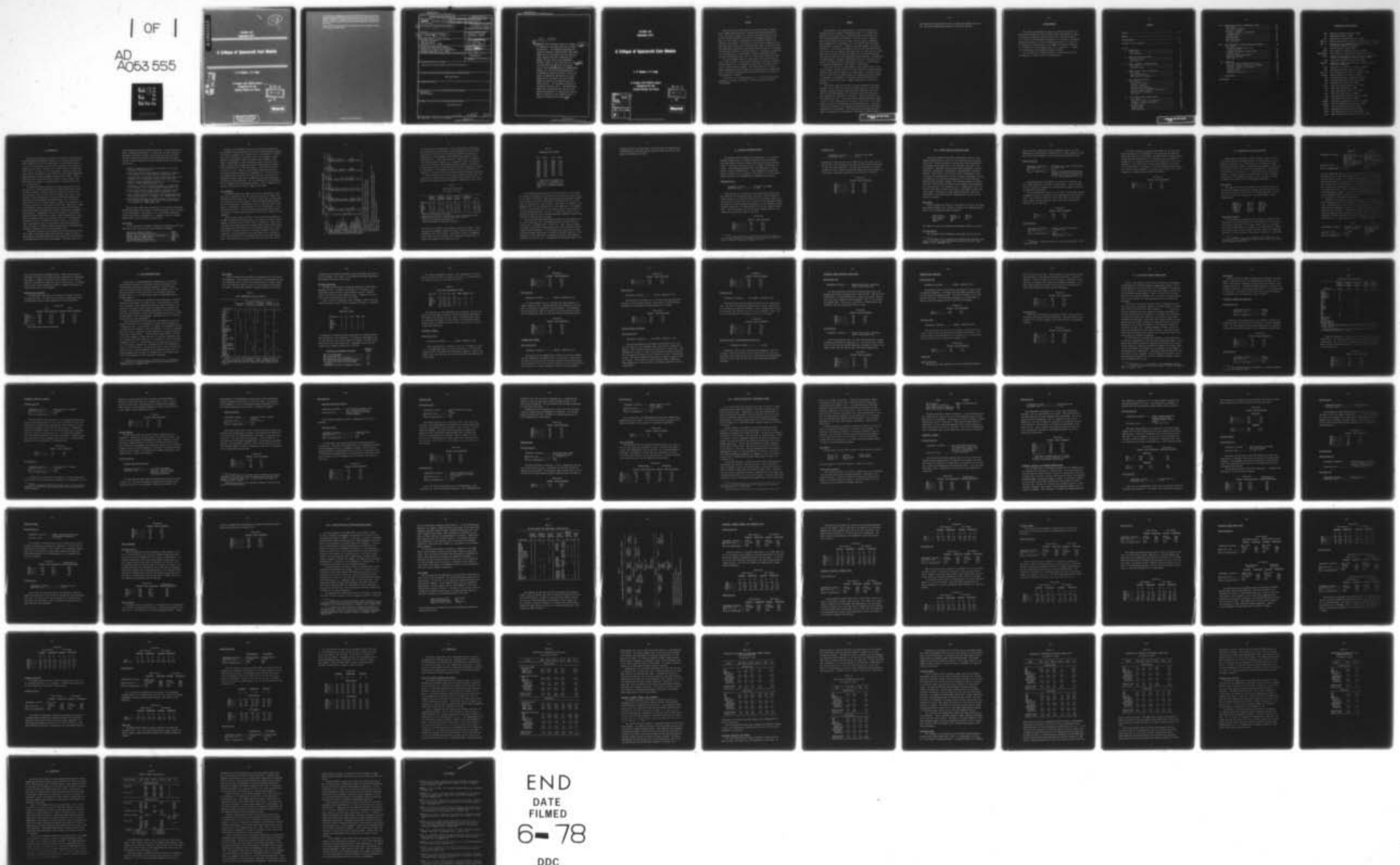
AD-A053 555 RAND CORP SANTA MONICA CALIF F/G 22/2
A CRITIQUE OF SPACECRAFT COST MODELS. (U)
SEP 77 J A DRYDEN, J P LARGE F49620-77-C-0023
UNCLASSIFIED RAND/R-2196/1-AF NL

| OF |

AD
A053 555



END
DATE
FILMED
6-78
DDC

13
SC

R-2196-1-AF
September 1977

A Critique of Spacecraft Cost Models

J. A. Dryden, J. P. Large

A Project AIR FORCE report
prepared for the
United States Air Force

Rand
SANTA MONICA, CA. 90406

The research reported here was sponsored by the Directorate of Operational Requirements, Deputy Chief of Staff/Research and Development, Hq. USAF under Contract F49620-77-C-0023. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation hereon.

Published by The Rand Corporation

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ~~R-2196-AF~~ R-2196-1-AF	2. GOVT ACCESSION NO. 14 RAND/R-2196/1-AF	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 A Critique of Spacecraft Cost Models.		5. TYPE OF REPORT & PERIOD COVERED 9 Interim rept.,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 J. A./Dryden [redacted] J. P./Large		8. CONTRACT OR GRANT NUMBER(s) 15 F49620-77-C-0023
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Rand Corporation✓ 1700 Main Street Santa Monica, Ca. 90406		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 12 87p.
11. CONTROLLING OFFICE NAME AND ADDRESS Project AIR FORCE Office (AF/RDQA) Directorate of Operational Requirements Hq USAF, Washington, D.C. 20330		12. REPORT DATE 11 Sept [redacted] 977
		13. NUMBER OF PAGES 75
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

No restrictions

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Spacecraft
Cost Estimates

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

see reverse side

296 600 Gu

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

This Paper

Examines the estimation accuracy of a group of parametric cost models used for a variety of spacecraft. ~~For two major reasons~~ It reinforces the caveat of model builders that models should not be used mechanically but should reflect changing spacecraft characteristics: Weight, the most widely used independent variable, should be less constraining in the next generation of spacecraft with space-shuttle launching; and spacecraft are ~~and~~ becoming cheaper on a per-unit-of-performance basis. In estimating nonrecurring costs, none of the models are generally applicable to any subsystem except structure, but several SAMSO models are useful for estimating total nonrecurring cost. All the models do better in estimating recurring costs. The SAMSO models appear most reliable for the user who lacks detailed knowledge of a program and wishes to base an estimate on such characteristics as weight and maximum array output. (WH)

R-2196-1-AF
September 1977

A Critique of Spacecraft Cost Models

J. A. Dryden, J. P. Large

A Project AIR FORCE report
prepared for the
United States Air Force

Rand
SANTA MONICA, CA. 90406

PREFACE

This study was performed under the Project AIR FORCE (formerly Project RAND) supporting project "Analytical Methodology Research." It was initiated in response to concern at The Rand Corporation and the Cost Analysis Division, Directorate of Management Analysis, Hq USAF, over the validity of spacecraft cost estimates obtained from parametric cost models. The question is particularly relevant for the next generation of spacecraft, because weight, which is the most widely used independent variable in such models, should be less of a constraint for spacecraft launched by the space shuttle. In addition, standardization of components or increased use of existing components reduces spacecraft development costs, and to a lesser extent production costs.

The study suggests that cost models should not be used mechanically. The user who is familiar with spacecraft technology in general, and the spacecraft to be estimated in particular, can adjust the results to obtain useful estimates. The study should be of value to persons employing spacecraft models for estimating costs, persons who have to evaluate such estimates, and persons involved in building the next generation of models.

This report is a companion-piece to J. P. Large and Capt. K.M.S. Gillespie, *A Critique of Aircraft Airframe Cost Models*, R-2194-AF (forthcoming).

A047 181

SUMMARY

Most parametric cost models produce a statistical analysis of observed costs on a sample of homogeneous items. It is implicitly assumed that the future will not differ greatly from the past, and that equations derived from observed costs will allow an analyst to make valid estimates of future costs. For many types of equipment those assumptions are reasonable, but it is doubtful that they apply unreservedly to spacecraft. Spacecraft are much cheaper (in constant dollars) on a per-unit-of-performance basis now than they were fifteen years ago, and it is commonly anticipated that cost will decline further when the space shuttle allows some relaxation of the rigorous weight constraints imposed by current expendable launch vehicles. Consequently, it seemed timely to examine a representative group of parametric cost models to determine how well they estimate costs for a varied sample of spacecraft representing a wide range of technologies.

The intent was not to pass judgment on the relative worth of the various models. Because they were not all intended to perform the same function, they cannot be judged on a common basis. Our intent rather was to find out how the models compare for estimating particular kinds of spacecraft or subsystems, to note what precautions should be observed in using a model, and to suggest directions for future cost modeling.

The results reinforce the note of caution sounded by most model designers to the effect that their creations should not be used mechanically, because using the equations without modifying them as dictated by the characteristics of a particular spacecraft will often give estimates too inaccurate to be useful. That is especially true for nonrecurring costs. None of the models examined has general applicability for any subsystem except structure, but several of the SAMSO models are useful for estimating total nonrecurring cost. Recurring costs are less sensitive to program peculiarities and are much better estimated by all the models. For the user who lacks detailed knowledge of a program and is interested in obtaining an estimate based on

basic spacecraft characteristics such as weight and maximum array output, the various SAMSO models appear to be the most reliable.

ACKNOWLEDGMENTS

The authors acknowledge with gratitude the help provided by the people who developed the various models, made them available to Rand, and answered innumerable questions about how to use them properly: S. E. Levine of the Aerospace Corporation; E. N. Dodson of the General Research Corporation; W. Gruhl of Headquarters NASA; F. K. Fong, Lt. R. Townsend, and Martha Martin of the SAMSO Cost Analysis Division; E. R. Brussell of Science Applications, Inc.; and Capt. C. J. Rowher of the Directorate of Management Analysis, Hq USAF.

For any mistakes in using the models or interpreting the data, the authors, of course, take full responsibility.

CONTENTS

PRECEDING PAGE NOT FILMED BLANK

GLOSSARY OF SPACE VEHICLES

AEM	Applications Explorer Mission (NASA)
AE	Atmospheric Explorer (NASA)
ATS	Applications Technology Satellite (NASA)
DMSP 5D	Defense Meteorological Satellite Program, Block 5D (USAF)
DSCS II	Defense Satellite Communications System, Phase II (USAF and Defense Communications Agency)
DSP	Defense Support Program (USAF)
ERTS	Earth Resources Technology Satellite (NASA)
FLEETSATCOM	Fleet Satellite Communications System (U.S. Navy)
IDCSP	Initial Defense Communication Satellite Program; also IDCSP/A, an augmentation known as "Skynet" (USAF)
IMP	Interplanetary Monitoring Platform (NASA)
INTELSAT	Commercial communication satellite (Communications Satellite Corporation)
ITOS	Improved Tiros Operational Satellite (NASA)
MMS	Multimission Modular Spacecraft (NASA)
NATO III	NATO communications satellite (USAF and NATO)
Nimbus	Weather observation satellite (NASA)
OAO	Orbiting Astronomical Observatory (NASA)
OGO	Orbiting Geophysical Observatory (NASA)
OSO	Orbiting Solar Observatory (NASA)
P72-2	Space Test Program Vehicle P72-2 (USAF)
RAE	Radio Astronomy Explorer (NASA)
S-3	Space Test Program Vehicle S-3 (USAF)
SAS	Small Astronomy Satellite (NASA)
SMS	Synchronous Meteorological Satellite (NASA)
SRS	Solar Radiation Satellite (NASA)
SYNCOM	Synchronous Communications Satellite (NASA)
TACSAT	Tactical Communications Satellite (USAF)
TETR	Test and Training Satellite (NASA)
Tiros	Weather Observation Satellite (NASA)
VASP	Vela Advanced Satellite Program (USAF)
Vela	Small spin-stabilized sensor satellite (USAF)

I. INTRODUCTION

Statistically derived cost models often replicate costs incurred in past programs with admirable fidelity. If a new program does not depart significantly from its predecessors, a model should estimate its cost with acceptable accuracy; and in some areas of technology the change from one year to the next is so gradual that a cost model may have a useful life span of five to ten years. Aircraft airframe and engine models, for example, may be derived from relatively homogeneous populations that include equipment developed in the 1950s. Because spacecraft have evolved much faster, however, there is always some doubt about the validity of existing models for predicting the cost of a new spacecraft.

In constant dollars, spacecraft have been getting cheaper over the years on a cost-per-pound basis even though capability per pound has been increasing. Moreover, when the intent is to build a low-cost spacecraft, as in the Air Force S-3 program, that intent can be realized. The increased use of previously developed components reduces spacecraft development cost substantially, and also reduces production cost but to a lesser extent. Further, the availability of the space shuttle as a launch vehicle implies that weight may no longer be so dominant a design constraint; hence existing cost-estimating relationships based on weight may not apply to spacecraft designed for shuttle launch. Consequently, it may be a mistake to use existing spacecraft models uncritically, without careful consideration of program requirements; doing so may overstate the cost of new spacecraft for which low cost is an important design criterion. It therefore seems an appropriate time to review some of the better-known spacecraft cost models to determine their applicability to new systems that represent a departure from a long-established trend.

The models included in this review have been developed by the Air Force, NASA, and private industry for different reasons, but most of them approach the estimating problem in the same way and include many of the same spacecraft in their data samples. Most agree that each

major subsystem should be estimated separately, although they may not agree on subsystem definitions. All agree that the most important explanatory variable is weight and that very few others are useful. The models themselves, however, differ sharply and give different results. Those included in the survey are described in the following publications:

Simplistic Spacecraft and Booster Cost Models, S. E. Levine, Aerospace Corporation, 1977.

Advanced Cost Estimating and Synthesis Techniques for Avionics, E. N. Dodson et al., General Research Corporation, 1975.

Cost Estimating Relationships for GSFC Unmanned Satellites, D. B. Clemens et al., Goddard Space Flight Center, NASA, 1973.

Spacecraft Platform Subsystem Complexity Level Cost Estimating Model, W. Gruhl, NASA Headquarters, 1972.

Development of Cost Estimating Relationships for FLEETSATCOM, E. R. Brussell et al., Planning Research Corporation, 1974.

Manpower/Cost Estimation Model--Automated Planetary Projects, L. D. Kitchen, Science Applications, Incorporated, 1975.

Space and Missile Systems Organization Unmanned Spacecraft Cost Model, Third Edition, C. J. Rowher et al., SAMSO, USAF, 1975.

SAMSO Unmanned Spacecraft Cost Model--Updated Cost Estimating Relationships and Normalization Factors (An Interim Report), F. K. Fong et al., SAMSO, USAF, 1977.

Several other models were reviewed but not included in the survey because they appear less relevant to today's problems. They are listed in the Bibliography. Other models, e.g., the Aerospace Corporation computer-based model developed by H. G. Campbell, were not included because they are not available for general use.

TEST SAMPLE

In this evaluation we compare estimates, by subsystem and by total spacecraft, with costs incurred on six spacecraft programs:

Applications Explorer Mission	(AEM)
Applications Technology Satellite F	(ATS-F)
Defense Satellite Communications System Phase II	(DSCS II)
Defense Support Program Phase II	(DSP II)
Multimission Modular Spacecraft	(MMS)
Space Technology Program S-3 model	(S-3)

Initially, we intended to select as test cases only spacecraft not included in the data samples on which the various models are based. It turned out, however, that virtually all of the spacecraft for which data could be obtained are included in one or more samples. Consequently, we endeavored to select spacecraft that represent a wide range of technologies, so that the models would be exercised over a range of inputs that by design exceeded the bounds normally dictated by the characteristics of the data samples. AEM and S-3 are small, low-cost spacecraft. MMS is a large, modular spacecraft lower in cost than conventional vehicles of comparable size. ATS-F and DSCS II are communication satellites; the other spacecraft are sensor or experiment platforms. AEM, ATS-F, and MMS are three-axis stabilized; the others are spin-stabilized. All are earth-orbital and representative of hardware used in USAF space missions. Table 1 summarizes the technical characteristics used as inputs to the model.

TEST PROCEDURE

The test procedure was simply to use each of the models to estimate costs in whatever detail was called for and then to compare the estimates with the actual cost. The word "actual" must be viewed with some tolerance for several reasons. First, the AEM and MMS programs are still in progress. Although NASA and the contractors have a high degree of confidence in the estimates, it is still premature to treat them as actual costs. They are included because we are particularly interested in testing model performance on the class of spacecraft they represent.

Second, detail costs on AEM and S-3 were provided by Boeing and on MMS by Goddard Space Flight Center. We relied on secondary sources, however, for actual costs of ATS-F, DSCS II, and DSP II. Other organizations, both public and private, have collected those costs directly from contractors in the past, and to save time we chose not to repeat that effort. During the course of the study, we began to note discrepancies in data pertaining to the same spacecraft as reported by two or more organizations, even though they drew on the same primary data. The discrepancies are due to the fact that only total program

Table 1

TECHNICAL CHARACTERISTICS OF TEST-CASE SPACECRAFT

Characteristic	Unit	AEM	ATS-F	DSCS II	DSP II	MMS	S-3
Spacecraft type	---	Sensor	*Communication*	*Communication*	Sensor	Multiple	Sensor
Category	---	Experimental	Experimental	Operational	Operational	Experimental	Experimental
Stabilization	---	3-axis	3-axis	Spin	Spin	3-axis	Spin
Orbit	---	<Synch	Synch	Synch		<Synch	<Synch
Lifetime	mo	12	60	60	36	24	12
Structure wt	lb	47.7	718.4	290.5	287	524[a]	139.2
Thermal control wt	lb	2.9	126.5	29.0	32[b]	75[c]	22.4
Interstage wt	lb	---	97.0	59.5	28	---	12.8
TT&C wt (w/antenna)	lb	25.4	105	79.5	77	161	44.0
No. of commands	---	186	512	169	240	200[d]	127
Att. cont. electronics wt	lb	28.9	148	93.2	119.4	233	26.8
Pointing accuracy	deg	±1	±0.1	±0.2	---	±0.01	---
RCS propulsion wt	lb	8.9	160.2	60.0	80.0	---	---
Propellant wt	lb	10.6	100	120.0	194.4	---	---
Thrust	lbf	0.29	1[d]	1[d]	1[d]	---	---
Solar power[e]	watt	238	645	535	865	500	100
EPS wt (w/harness)	lb	70.7	619.6	312.3	540.5	538[f]	68.2
Solar array type	---	Paddle	Paddle	Body	Body[g]	Paddle	Paddle
Wiring harness wt	lb	12.0	180	---	---	139	31.8
Communications S/S wt[h]	lb	---	507.8	236.9	---	---	---
No. of transmitter chains	---	---	6	2	---	---	---
Radio frequency S/S wt	lb	8.1	316.6[d]	266.3[d]	77[d]	21	5.6
Data handling S/S wt	lb	16.2	104[d]	0[d]	0[d]	93	37.4
Antenna wt	lb	1.1	191.2	50.1	5.8	47	1

[a] Support and module structure weights are: 232 + 91 + 105 + 96 = 524.

[b] Estimated at 10 percent of combined structure and thermal control weight.

[c] Estimated at 12.5 percent of combined structure and thermal control weight.

[d] Approximate data.

[e] Power values are maximum array output, beginning of life, except for AEM, which is end of life.

[f] MMS has no unique solar array; the weight shown includes 117 lb for array and drive.

[g] Paddles are also used but are a minor part.

[h] Includes antennas.

cost can be known with precision. Allocations between nonrecurring and recurring cost and among the various subsystems can be arbitrary. Contractors are likely to use differing allocation procedures and definitions of cost elements--system engineering, quality control, reliability, etc. Some companies treat a certain cost as a program-level expense; others assign it to a subsystem. Those varying practices are reflected in the estimating models examined. Some models attribute most costs to subsystems and add a small program cost; others do the opposite. To minimize the effect of such differences in the analysis, all program costs were prorated among the hardware subsystems.

Table 2 shows the actual costs used in computing deviations. The table lists no nonrecurring costs for MMS, because several NASA programs have contributed to the development of MMS hardware and it would

Table 2

TEST CASE ACTUAL COSTS[a]

(In million $ 1976)

	Structure Thermal Interstage		Telemetry, Tracking, and Command		Attitude Control Subsystem		Electrical Power Subsystem		Combined Communications and TT&C		Total[b]	
Spacecraft	NR	R	NR	R	NR	R	NR	R	NR	R	NR	R
AEM	0.7	0.4	0.7	0.5	0.5	0.7	0.4	0.6	---	---	2.3	2.3
ATS-F	11.5	2.6	---	---	23.4	8.3	2.9	1.7	16.7	8.7	54.6	21.3
DSCS II	6.2	1.0	---	---	17.5	2.6	3.6	1.6	29.3	5.6	56.6	10.8
DSP II	7.8	1.7	10.5	2.9	11.2	4.1	18.9	5.3	---	---	48.4[c]	14.0
MMS	---	0.9	---	2.7	---	1.7	---	3.7	---	---	---	9.0
S-3	1.8	0.7	2.2	0.6	1.1	0.3	0.8	0.4	---	---	5.9	2.0

NOTE: NR = nonrecurring; R = recurring.

[a]Recurring cost is the cost of the first unit. Where it was necessary to derive first-unit cost from lot cost, a 95 percent learning curve was used.

[b]Totals are not adjusted for rounding errors.

[c]Has not been adjusted for inheritance from Phase I.

be difficult to identify nonrecurring cost with any accuracy. Aerospace ground equipment, launch, and orbital operation costs are not included in any of the numbers. Most models contain a recommended price index, but in the interest of consistency the index given in Table 3 was applied to all base-year costs.

Table 3

SPACECRAFT PRICE INDEX[a]

Year	Index	Year	Index
1958	3.13	1968	1.83
1959	2.97	1969	1.69
1960	2.84	1970	1.60
1961	2.68	1971	1.53
1962	2.52	1972	1.45
1963	2.35	1973	1.41
1964	2.24	1974	1.21
1965	2.12	1975	1.07
1966	2.02	1976	1.00
1967	1.91		

[a]Based on the procedure described in H. G. Campbell, *Aerospace Price Indexes*, The Rand Corporation, R-568-PR, December 1970.

The following sections include a brief description of each model, the spacecraft included in the data base for the model, and the results of our tests of the model. Where the equations were derived by regression analysis, we show the coefficient of determination (R^2) and the level of significance of the variables. The former is a measure of the goodness of fit of the regressed line to the sample data. For example, an R^2 of 1.0 would mean that all the observed points in the sample are on the least-squares line. The level of significance indicates the probability that the results obtained using the estimating relationship could be obtained strictly by chance.

Dollar and percentage deviations are shown for each subsystem and for total spacecraft cost. Percentage deviation is defined here as (actual cost - estimated cost) ÷ actual cost. Thus a positive deviation means that the model underestimates cost, and a negative deviation signifies an overestimate. A zero estimate, the lowest that is theoretically possible, would give a positive 100 percent deviation. Overestimates, on the other hand, are unbounded, and very large negative deviations can and do occur. In examining the deviations shown in the

ensuing sections, one should keep in mind that they are biased toward overestimates and that the absolute costs on which the deviations are based are sometimes quite small.

II. AEROSPACE CORPORATION MODEL

The simplest model considered was developed by S. E. Levine at Aerospace Corporation for "a system tradeoff study that required rapid approximate costing of numerous satellite and booster combinations."[1] The model is unique in that it is based on estimates, not actuals. The estimates were made using the SAMSO model on "about thirty conceptual SATCOM designs." Being designed so narrowly and based on synthetic data, the model is not useful for a broad range of systems and cannot be recommended for communication satellites.

NONRECURRING COST

Independent variable	Spacecraft dry weight
Functional form	$Y = aX^b$

Nonrecurring cost is defined to include aerospace ground equipment (AGE) and two development model spacecraft. Data provided by Levine allowed us to delete AGE costs from the estimates, and we subtracted twice the first-unit cost to adjust for the development models. The results are mixed, showing overestimates for the cheapest and most expensive spacecraft, and underestimates for the two "standard" spacecraft. On a dollar basis the best and worst estimates were for two communication satellites, DSCS II and ATS-F.

	Deviations	
	Percent	Cost ($ million)
AEM	-504	-11.6
ATS-F	-41	-22.6
DSCS II	11	6.3
DSP	34	16.4
S-3	-234	-13.8

[1] S. E. Levine, *Simplistic Spacecraft and Booster Cost Models*, The Aerospace Corporation, El Segundo, Calif., Satellite Systems Division, V, TOR-0077 (2404-30)-3, February 11, 1977.

RECURRING COST

Independent variable .... Spacecraft dry weight
Functional form .... Y = aX

Estimates of recurring cost are too high for all test cases, but for AEM and DSP II the estimates are as good as those obtained using some of the other models described. The high dollar-deviations on ATS-F and MMS--two very different spacecraft--suggest that the relevance of this model to particular spacecraft may be difficult to predict.

	Deviations	
	Percent	Cost ($ million)
AEM	-26	-0.6
ATS-F	-87	-18.4
DSCS II	-46	-5.0
DSP	-17	-2.4
MMS	-138	-12.4
S-3	-125	-2.5

III. GENERAL RESEARCH CORPORATION MODEL

The General Research Corporation model differs from all other studies discussed here in that it is not concerned with total spacecraft cost.[1] We have included it because some of the techniques are of interest and the data base is quite different from that in the other models. GRC treats several space system components in detail: computers, transceivers, traveling-wave tube amplifiers, and multiplexers. A GRC review of the attitude control subsystems in about 10 spacecraft indicated that "each was virtually custom-made" and that the sample was not sufficiently homogeneous for detailed analysis. Equations were developed, however, for estimating design and development cost, nonrecurring cost (which includes design and development), and recurring cost at the subsystem level. Program-level costs, calculated on the basis of data in the report, were added to obtain the totals shown. The weight and type (spin-stabilized or three-axis stabilized) of an attitude control subsystem (ACS) are the only explanatory variables.

DATA SAMPLE

Eleven programs are included in this model's data base, including four manned programs, four scientific programs, two communication programs, and one operational sensor platform:

Apollo Block I	Mariner	DSCS II
Apollo Block II	Pioneer F/G	ATS A/E
Lunar Module	OSO I	Vela
Gemini	OGO	

The sample for each cost-estimating relationship (CER) is not stated.

ATTITUDE CONTROL

The attitude control subsystem in this model does not include

[1]E. N. Dodson et al., *Advanced Cost Estimating and Synthesis Techniques for Avionics*, General Research Corporation, CR-2-461, Santa Barbara, Calif., September 1975.

reaction control components, such as thrusters, valves, and tanks. Consequently, deviations were computed only for those programs in which the cost of those components could be deleted from spacecraft cost.

Nonrecurring Cost

Independent variables[2] ...	Recurring cost, type of stabilization
Functional form	$Y = aW^b(1 + cX)$
R^2	0.52
Level of significance	Could not be calculated because the degrees of freedom are not stated in the GRC report. For recurring cost, t = 2.4; for stabilization, t = 1.7.

Nonrecurring cost is estimated as a function of recurring cost and a dummy variable for the type of stabilization. Since recurring cost is a function of weight and a dummy variable, weight is actually the dominant variable here.

From the deviations below, it is clear that the GRC model does not accommodate the type of attitude control subsystems on low-cost spacecraft. The estimate of DSCS II, on the other hand, is much better. Those results are what one would expect, given the very expensive spacecraft in the data base.

	Deviations	
	Percent	Cost ($ million)
AEM	-3660	-14.7
DSCS II	40	5.8
S-3	-437	-4.7

Recurring Cost

Independent variables	Weight, type of stabilization
Functional form	$Y = aW^b(1 + cX)$
R^2	0.56
Level of significance	Weight: t = -3.7 Stabilization: t = 0.3

[2]Independent variables are given in the order they appear in the functional form.

It is clear from the t-statistics that weight is the only significant variable, but the estimates for recurring cost are generally better than those for nonrecurring. The CER is based on high-precision attitude control systems; thus it is reasonable for the estimate of the MMS ACS to be relatively good and for the AEM and S-3 to be overestimated. It is curious that a fairly good estimate of recurring cost for AEM leads to a deviation of over 3000 percent in nonrecurring cost, while a poorer estimate of recurring cost for DSCS II is transformed into an improved nonrecurring cost estimate.

	Deviations	
	Percent	Cost ($ million)
AEM	-23	-0.1
DSCS II	59	1.5
MMS	24	0.4
S-3	-157	-0.4

IV. GODDARD SPACE FLIGHT CENTER MODEL

Goddard Space Flight Center (GSFC) published a report in 1973 containing equations considered suitable for estimating the cost of spacecraft platforms, i.e., "that portion of the spacecraft which provides structural integrity, data processing capability, power, and stabilization control for the on-board experiments."[1] The platform is estimated in its entirety, i.e., subsystems are not treated separately. A number of equations are provided, each with a somewhat different set of independent variables so that the user can choose an equation for which he has all the needed information.

DATA SAMPLE

The sample consists of the completed and (in 1973) nearly completed GSFC programs listed below. Because only GSFC spacecraft are included, the model is said to reflect the Goddard manner of doing business and may not be applicable to programs managed by other organizations.

RAE A&B	OGO A-F	TIROS N
NIMBUS I&II	OSO D-G	ITOS A,B,C
NIMBUS B-2	OSO H	IMP A,B,C
NIMBUS B	ATS I-V	IMP D&E
NIMBUS D	SAS A&B	IMP F&G
TETR C&D	OAO C	IMP I

ESTIMATING EQUATIONS

The two equations considered most acceptable by GSFC have the characteristics described below, but those equations were not used in this survey because some of the inputs required were not available. The number of experiments, for example, is not applicable on communication satellites, and gross weight and power capacity are sometimes difficult to come by because of definitional differences. Equivalent

[1] D. B. Clemens et al., *Cost Estimating Relationships for GSFC Unmanned Satellites*, Goddard Space Flight Center, X-213-73-66, Greenbelt, Maryland, February 1973.

	Equation 1	Equation 2
Independent variables ...	Equivalent units Spacecraft gross weight C&DH weight Power capacity Number of experiments Type of control system	Equivalent units Spacecraft net weight C&DH weight Number of experiments Type of control system
Functional form	$Y = aT^bU^cV^dW^eX^fZ^g$	[illegible]
R^2	0.97	0.97
Level of significance ...	<0.01	<0.01

units are simply the ratio of all costs to the first flight unit. To estimate the cost of the first flight unit only, a value of one equivalent unit would be used. To estimate total program cost, a user must estimate how the cost of each major program element (design and development, thermal model, prototype model, etc.) relates to the cost of the first flight unit, and then must sum the individual ratios to obtain total equivalent units. Thus, to obtain recurring spacecraft cost is a straightforward procedure, but to obtain nonrecurring cost requires a major judgmental input on the part of the user. Only recurring costs are considered in the comparisons shown here.

Estimates of recurring cost were made using two of the eight alternative equations given in the appendix to the GSFC report. These equations, identified as D(1) and D(4), were chosen because their statistical properties are comparable to those of the preferred equations, and the input data were available. The number of inputs for the alternative equations ranges from two (weight and equivalent units) to six, and presumably, as more variables are used, the estimate more closely represents the cost of a particular spacecraft. It appears, however, that

	D(1)	D(4)
Independent variables ...	Equivalent units, net Spacecraft weight	Equivalent units, net Spacecraft weight C&DH weight
Functional form	$Y = aW^bX^c$	[illegible]
R^2	0.96	0.97
Level of significance ...	<0.01	<0.01

all of the equations give similar results. Where input data were available, all eight of the equations were tested and the differences were small: a range of $6 million to $6.6 million on S-3 and $17.4 million to $18 million on MMS (all costs in 1973 dollars). It appears that the only really significant variable is weight; the others contribute very little to the estimate.

RECURRING COST ESTIMATES

As shown below, estimates are essentially the same for both of the equations used. All spacecraft are greatly overestimated; thus the GSFC model does not appear appropriate for USAF spacecraft.

	Deviations			
	D(1)		D(4)	
	Percent	Cost ($ million)	Percent	Cost ($ million)
AEM	-182	-4.1	-182	-4.1
ATS-F[a]	-110	-15.9	-103	-14.9
DSCS II[a] ...	-246	-12.8	-240	-12.5
DSP II	-50	-7.1	-47	-6.6
MMS	-181	-16.4	-182	-16.5
S-3	-334	-6.7	-335	-6.7

[a]Excluding communications subsystems.

V. NASA HEADQUARTERS MODEL

Werner Gruhl, of NASA Headquarters, Washington, D.C., has published several versions of a spacecraft cost model intended for use in evaluating new spacecraft proposal estimates. The most recent that was available to Rand is Version III, dated November 1972.[1] The model can be used for both earth-orbital and planetary spacecraft platform costs, i.e., all costs except those for experiments and experiment support.

Estimating equations are provided for seven subsystems: structure (mechanical and thermal), attitude control, liquid propulsion, telemetry and command, relay communication payload, parabolic antenna, and solar power (includes central control and regulation, batteries, and cabling). Nonrecurring cost estimate adjustments are provided to take into account the amount of design and development required (e.g., mostly new development, half new development, repackaging only, etc.) and the testing and test unit requirements.

Both nonrecurring and recurring costs are estimated for each subsystem on the basis of one independent variable (usually weight) and a complexity level. For structure, for example, the estimating variable is weight and two complexity levels are defined. As an aid in choosing the correct level, spacecraft of each complexity are listed along with their major characteristics. TIROS-M, OSO-G, OSO-H, DSCS II, and SRS are cited as examples of spacecraft with a structural complexity level of 1; Pioneer F&G, ATS-F, OAO, ATS 1-5, and OGO I-III have a structural complexity level of 2. The difference in recurring unit cost for 100 lb of structure is substantial: $215,000 at Level 1 and $630,000 at Level 2 (in 1972 dollars). To choose the correct level, the user must have more than a cursory knowledge of the spacecraft whose cost is being estimated, and the model is intended for use by analysts with a basic understanding of current spacecraft technology.

---

[1] *Spacecraft Platform Subsystem Complexity Level Cost Estimating Model*, Version III, National Aeronautics and Space Administration, Washington, D.C., November 1972.

DATA SAMPLE

Table 4 presents the data sample by complexity level for five of the subsystems. Liquid propulsion and parabolic antenna CERs use only one complexity level, and their data samples were not stated. Apparently, the same data sample was used for nonrecurring and recurring cost CERs. The data base primarily comprises scientific satellites,

Table 4

NASA HEADQUARTERS CER DATA SAMPLES

	Structure, Thermal		Attitude Control Subsystem			Telemetry, Tracking, & Command		Relay Communi-cations		Solar Power		
Spacecraft	1	2	1	2	3	1	2	1	2	1	2	3
TIROS M	x			x		x				x		
OSO-G	x			x		x						
OSO-H	x									x		
DSCS II	x			x		x		x		x		
SRS	x		x			x						
PIONEER F+G		x			x	x						
ATS-F		x			x	x		x		x		
OAO		x										
ATS 1-5		x										
OGO I-III		x		x								
MARINER 69		x			x		x				x	
MARINER 71		x									x	
Vela			x									
SYNCOM			x					x				
IDCSP			x					x				
ATS F-4 w/OGC			x									
ATS F-3			x			x						
VASP				x								
ATS F-2, MG				x								
LUNAR ORBITER					x							
NIMBUS D					x							
VIKING ORBITER					x		x		x		x	
OAO B					x		x					x
ATS/SS								x				
IDCSP/A								x				
ERTS A+B												x

NOTES: 1, 2, and 3 are complexity levels. Samples pertain to both nonrecurring and recurring CERs. Liquid propulsion and parabolic antenna CERs have only one complexity level; sample was not stated.

including several planetary programs; low-cost programs, such as S-3, are not included. As a result, it was expected that this model would overestimate the low-cost test cases.

ESTIMATING PROCEDURE

The CERs in this model are presented graphically rather than in mathematical form. In general the graphs are curvilinear on full logarithmic grids and reflect some economies of scale. Separate curves are plotted for each complexity level. Goodness of fit statistics were not included for any of the CERs.

Table 5 shows the complexity levels assigned to each of the test cases on the basis of the criteria previously discussed. In addition

Table 5

COMPLEXITY LEVELS

Spacecraft	ST	ACS	TT&C	COMM	EPS
AEM	1	1	1	----	1
ATS-F	2	3	1	1	1
DSCS II	1	2	1	1	1
DSP II	1	3	1	---	1
MMS	1	3	1	----	1
S-3	1	1	1	---	1

to complexity, the model provides nonrecurring cost estimate adjustment procedures in two categories: (1) design and development, and (2) test and test units; each category is assumed to include 50 percent of the total nonrecurring cost. Adjustment factors for the design and development category are as follows:

Design and Development Variations	Redesign Factor
Mostly new development	1.5
Half new development	1.3
New design but little development	1.0
Half new design and repackaging remainder	0.9
One quarter new design and repackaging remainder	0.8
Repackaging only with no changes in design	0.6

The terms "development," "design," and "repackaging," not being defined in Gruhl's report, are difficult to apply. In estimating the test cases we used the factors shown in Table 6.

Table 6

DESIGN AND DEVELOPMENT FACTORS

Spacecraft	S+T	T+C	ACS	PROP	COMM	ANTENNA	EPS
AEM	0.8	0.8	0.8	0.8	---	---	1
ATS-F	1.3	1.0	1.3	1.3	1.3	1.3	1
DSCS II	1.3	1.0	1.3	1.3	1	1	1
DSP II	1.0	1.0	1.0	1.0	---	---	1
MMS	0.9	0.9	1.3	---	---	---	1
S-3	0.8	0.8	0.8	---	---	---	1

The test and test unit adjustment are less formal; only the composition of this phase is shown as a guide to possible adjustments. The nominal case includes two test units. Following Gruhl's advice we subtracted 150 percent of the first-unit cost estimate from the nonrecurring cost estimate in order to back out the cost of a protoflight model spacecraft.

STRUCTURE, THERMAL

Nonrecurring Cost

Independent variables .... Weight, complexity level

Gruhl assigned ATS-F a complexity level of 2 and DSCS II a level of 1. We judged the other test cases to be Level 1. If ATS-F were judged a Level 1 the estimate would be greatly improved. With no complexity level less than one, the low-cost satellites are significantly overestimated.

	Deviations	
	Percent	Cost ($ million)
AEM	-87	-0.6
ATS-F	-77	-8.9
DSCS II	-26	-1.6
DSP II	14	1.1
S-3	-133	-2.4

Recurring Cost

Independent variables .... Weight, complexity level

The ATS-F estimate is out of line with the others because of a higher complexity level. The MMS deviation is influenced by the fact that its structure is produced as separate modules. The reasonable dollar deviations for DSCS II and DSP II and the good low-cost (AEM and S-3) performance show that this CER could have wide applicability.

	Deviations	
	Percent	Cost ($ million)
AEM	-72	-0.3
ATS-F	-104	-2.7
DSCS II	9	0.1
DSP II	43	0.7
MMS	-172	-1.5
S-3	0	0.0

TELEMETRY AND COMMAND

Nonrecurring Cost

Independent variables .... Weight, complexity level

The results for the communication satellite for T&C are combined with the communication subsystem later in this section. The results for DSP II are fair, but the low-cost satellites are estimated poorly. The Y-intercept of the cost-vs-weight estimating curve is approximately $1.5 million, so all small systems are likely to be overestimated.

	Deviations Percent	Cost ($ million)
AEM	-424	-3.2
DSP II	17	1.8
S-3	-149	-3.3

Recurring Cost

Independent variables .... Weight, complexity level

This CER does not estimate any of the test cases extremely well, nor does it err by extreme amounts. Like others, it underestimates the middle and high range and overestimates the low range.

	Deviations Percent	Cost ($ million)
AEM	-84	-0.4
DSP II	39	1.1
MMS	20	0.5
S-3	-105	-0.7

ATTITUDE CONTROL SUBSYSTEM

Nonrecurring Cost

Independent variables ..... Dry weight, complexity level

The NASA HQ estimating relationship overestimates five of the six test cases for this subsystem, given the levels of complexity in Table 6. ATS-F and DSP II would all do better at a lower level. The assignment of a Level 3 to DSP II was influenced by pointing accuracy, but the subjective element in such decisions can result in substantial errors. The low-cost satellites are again too small to relate to the data sample. (The deviations include reaction control components where appropriate; reaction control is estimated separately, as discussed below.)

	Deviations	
	Percent	Cost ($ million)
AEM	-709	-3.2
ATS-F	-119	-27.7
DSCS II	49	8.6
DSP II	-65	-7.4
S-3	-195	-2.1

Recurring Cost

Independent variables ..... Dry weight, complexity level

The results here are much better than those for the nonrecurring case. The dollar deviations for AEM and S-3 are small, and the percent deviations for AEM are reasonable. DSP II and MMS appear to have been assigned high complexity levels, but the assignments comply with the rules indicated by the analogous satellites in the model.

	Deviations	
	Percent	Cost ($ million)
AEM	11	0.1
ATS-F	45	3.8
DSCS II	-62	-1.6
DSP II	-65	-2.7
MMS	-275	-4.7
S-3	-91	-0.2

Reaction Control: Nonrecurring and Recurring

Independent variable .... Thrust

Complexity levels are not used with this subsystem. Two cost-vs-thrust curves are provided, one for nonrecurring cost and one for recurring. The curves are very flat in the region below approximately 30 lbf of thrust; then cost per lbf of thrust increases as thrust increases.

ELECTRICAL POWER SUBSYSTEM (SOLAR POWER)

Nonrecurring Cost

Independent variables ..... Maximum array output, complexity level, stabilization type

For spin-stabilized satellites with body-mounted arrays, the maximum array output is doubled before using the CER. Even with this doubling DSP II is underestimated by a large dollar amount, indicating an incorrect complexity level assignment. DSCS II, in contrast, is estimated well. The low-cost satellites are significantly overestimated; thus the doubling hurts the S-3 case.

	Deviations	
	Percent	Cost ($ million)
AEM	-698	-2.6
ATS-F	-26	-0.8
DSCS II	-11	-0.4
DSP II	80	15.2
S-3	-286	-2.3

Recurring Cost

Independent variables ..... Maximum array output, complexity level, stabilization type

The dollar deviation for S-3 is less than $50,000 here, and the percentage deviations are generally low. The high deviation on MMS reflects the fact that the MMS subsystem is designed to handle a much higher output than the nominal value (500 watts) assumed here.

	Deviations	
	Percent	Cost ($ million)
AEM	-43	-0.3
ATS-F	-11	-0.2
DSCS II	-73	-1.2
DSP II	25	1.3
MMS	58	2.2
S-3	0	0.0

COMMUNICATIONS SUBSYSTEM

Nonrecurring Cost

Independent variables .... Weight, complexity level

The deviations below include T&C and the parabolic antenna, which is estimated separately. The design and development adjustment factor for ATS-F made the estimate poorer. The DSCS II estimate on the other hand is very good. This inconsistent performance is surprising, especially since both spacecraft are in the CER's data sample.

	Deviations	
	Percent	Cost ($ million)
ATS-F	-199	-33.3
DSCS II	-10	-3.0

Recurring Cost

Independent variables .... Weight, complexity level

The results here are better on the average, but with both spacecraft in the data base the deviations are higher than expected. The opposite signs of the deviations are an indication of a slope problem, but no conclusions can be drawn from a sample of two.

	Deviations	
	Percent	Cost ($ million)
ATS-F	22	1.9
DSCS II	-50	-2.9

TOTAL COST

Nonrecurring Cost

The deviations below compare the sum of the subsystem estimates

with the total actual costs. Three systems are overestimated by more than 100 percent. The low-cost systems are the worst, as would be expected. The ATS-F results reflect the choice of complexity levels, and were not helped by the design and development adjustment. It is clear that the Gruhl procedures can be used only by persons with a good understanding of the model and the subsystems.

	Deviations	
	Percent	Cost ($ million)
AEM	-423	-9.6
ATS-F	-130	-70.7
DSCS II	6	3.6
DSP II	22	10.7
S-3	-171	-10.1

Recurring Cost

Recurring cost estimates are generally better, partly because of offsetting overestimates and underestimates. The model tends to overestimate cost, but the estimates may be satisfactory for preliminary planning.

	Deviations	
	Percent	Cost ($ million)
AEM	-40	-0.9
ATS-F	13	2.8
DSCS II	-51	-5.6
DSP II	4	0.5
MMS	-39	-3.5
S-3	-45	-0.9

VI. PRC SYSTEM SCIENCES COMPANY MODEL

The U.S. Navy funded a study in 1973 to develop cost-estimating relationships for the Fleet Satellite Communication system. The relationships were to provide a basis for an independent cost estimate of that system. A two-volume final report was issued in January 1974 by PRC Systems Sciences Company.[1] Much of the report is concerned with the cost of ground terminals, but it includes a detailed description of the derivation of estimating equations for each spacecraft subsystem.

Initially, it was stated that the "cost of communication satellites may relate to frequency, numbers of channels, weight, structure, power (solar and battery) and other variables. . . ." In the model that was developed, the major explanatory variable was weight, but several new variables were introduced. For example, the cost-effect of solid state electronics, especially in the form of metal-oxide-semiconductor technology, can be taken into account using as an independent variable either the number of equivalent discrete electronic pieceparts or the electronic density of the component, measured in discretes per cubic inch. Lacking knowledge of either, we did not adjust the estimates to reflect their influence. The results shown here therefore probably do not reflect the accuracy that could be obtained with more detailed information.

The PRC model also discusses the treatment of cost uncertainty in the use of aggregation of the individual subsystem estimates. Their method uses the Beta probability distribution and Monte Carlo simulation as applied to subjective probability estimates of the most likely, lowest, and highest cost estimates for a subsystem, and the shape of the subsystem cost distribution. The results shown below have not had the benefit of that treatment. The only change we have made to estimates produced by the model is to add a 10 percent allowance for general and administrative costs.

---

[1] E. R. Brussell et al., *Development of Cost Estimating Relationships for FLEETSATCOM*, PRC System Sciences Company, R-1800, Los Angeles, Calif., January 4, 1974.

DATA SAMPLE

The data sample includes 15 programs and 31 different satellite types.[2] Thirteen of the 31 are communication satellites, one is a lunar orbiter and the remainder are operational or scientific earth-orbiting satellites. It therefore seemed legitimate to explore the possibility that the model would be applicable to a fairly broad range of spacecraft. The sample of spacecraft used to derive estimating relationships for each subsystem is shown in Table 7.

STRUCTURE, THERMAL AND INTERSTAGE

Nonrecurring Cost

Independent variable	Weight
Functional form	$Y = aX^b$
R^2	0.57
Level of significance	0.005

Estimates of the nonrecurring cost of structure, thermal and interstage, show low-cost spacecraft (AEM and S-3) greatly overestimated. All other spacecraft are underestimated, but the communications satellites (ATS-F and DSCS II) are estimated relatively well.

	Deviations	
	Percent	Cost ($ million)
AEM	-145	-1.0
ATS-F	16	1.9
DSCS II	9	0.6
DSP II	31	2.4
S-3	-96	-1.7

Recurring Cost

Independent variable	Weight
Functional form	$Y = aX^b$
R^2	0.44
Level of significance	>0.1

[2] In the terminology used here INTELSAT is a program; INTELSAT I, II, etc., are satellite types.

Table 7

FLEETSATCOM CER DATA SAMPLES

Satellite	Structure, Thermal, Interstage NR	Structure, Thermal, Interstage R	Telemetry, Tracking, & Command NR	Telemetry, Tracking, & Command R	Electrical Power Subsystem NR	Electrical Power Subsystem R	Communications Subsystem NR	Communications Subsystem R	Reaction Control Subsystem R^a
TACSAT	x	x	x	x	x	x	x	x	x
INTELSAT I	x								
INTELSAT II	x								
INTELSAT III	x				x				
INTELSAT IV	x	x	x	x	x		x	x	
ATS-A	x				x	x			
ATS-B	x	x	x	x		x			
ATS-C					x	x			x
ATS-D	x		x	x		x			
ATS-E		x			x				
SYNCOM					x		x	x	
IDCSP/A	x				x				
DSCS II	x	x	x	x	x		x	x	x
DSP					x				
Vela	x				x				
VASP	x				x				
OGO	x				x				
Lunar Orbiter	x				x				
Satellite S_1			x	x					
Satellite P_1							x	x	
Special satellite									x
Proposed satellite									x

NOTE: Other satellites in model's data base: OAO A,B,C; OSO A,B,C,D,E; SAS A,B,C; RAE A,B.

[a] Nonrecurring Reaction Control and all Attitude and Velocity Control CER data samples were unavailable in the model.

Generally, estimates of recurring cost are better than those discussed above. The tendency shown below is to overestimate rather than underestimate cost, but dollar deviations are small except for MMS. MMS is greatly overestimated because of its heavy structure relative to other spacecraft.

	Deviations	
	Percent	Cost ($ million)
AEM	-4	0
ATS-F	-51	-1.3
DSCS II	-95	-1.0
DSP II	-6	-0.1
MMS	-346	-3.0
S-3	-59	-0.4

TELEMETRY, TRACKING & COMMAND

Nonrecurring Cost

Independent variable	Weight, number of commands[3]
Functional form	$Y = aW^bX^c$
R^2	0.81
Level of significance	0.1

The data base for TT&C consisted of five communication satellites and one unidentified spacecraft, but in practice TT&C and mission communications on communication satellites are often treated as one subsystem, then separated arbitrarily for cost purposes. Consequently, the data are somewhat suspect, but the CER developed does a reasonably good job on the two low-cost spacecraft. All three TT&C subsystems below are underestimated (DSP II by about $3 million). Deviations were not calculated for the two communication satellites; a combined TT&C/COMM cost for ATS-F and DSCS II is discussed later.

	Deviations	
	Percent	Cost ($ million)
AEM	8	0.1
DSP II	28	3.0
S-3	19	0.4

Recurring Cost

Independent variable	Weight, number of commands
Functional form	$Y = aW^bX^c$
R^2	0.56
Level of significance	>0.25

As shown below, the equation overestimates in various degrees the cost of TT&C in the three spacecraft intended to be inexpensive. DSP II,

[3] Number of equivalent discrete electronic parts is an alternative variable. We used the two shown above because data on those are more easily available.

however, is underestimated by over $1 million, which when added to the error in the nonrecurring cost estimate gives a total of over $4 million for TT&C alone. The high-data-rate communication equipment used for sensor data transmission apparently differs enough from that in the sample to cause substantial error.

	Deviations	
	Percent	Cost ($ million)
AEM	-19	-0.1
DSP II	41	1.2
MMS	-27	-0.7
S-3	-74	-0.5

ATTITUDE CONTROL

The PRC model breaks the attitude control subsystem into two components: attitude and velocity control, and reaction control. The two are not well defined, but presumably the first consists of control electronics, momentum wheels and controls, attitude and velocity sensors, and ancillary equipment; the second then consists of the thrusters, tankage, valves, and other plumbing of a hydrazine or hydrogen peroxide reaction control system. We estimated each component separately, then combined them to compute the deviations.

Nonrecurring Cost

Attitude and velocity control

Independent variable	Total satellite weight.
Functional form	Not given. Separate curves shown for 3-axis and spin-stabilized spacecraft.

The model provides three CERs for estimating attitude and velocity control cost. The other independent variables are pointing accuracy (when less than 0.1°) and the number of equivalent discretes. We

chose weight as the independent variable based on data availability and the technical characteristics of the test cases. No statistics on the goodness of fit of this CER were derived; loglinear curves of cost versus weight were plotted based on engineering judgment.

Reaction control[4]

Independent variable	Propellant weight, pointing accuracy
Functional form[5]	Y = a + bW + cX
R^2	0.59
Level of significance	>0.25

When nonrecurring costs for the attitude and velocity control and reaction control subsystems are summed, the deviations for AEM and S-3 are so great that the inapplicability of the model to those spacecraft is obvious. Both are greatly overestimated. ATS-F and DSCS II, on the other hand, are greatly underestimated. The inclusion of pointing accuracy as an explanatory variable in the attitude and velocity control CER would appear to improve estimating accuracy and is reasonable from an engineering point of view.

	Deviations	
	Percent	Cost ($ million)
AEM	-1570	-7.1
ATS-F	43	10
DSCS II	52	9.1
DSP II	16	1.8
S-3	-336	-3.6

[4] S-3 and MMS data do not include chemical-based reaction control subsystems. The other test cases use hydrazine, and the data below relate to hydrazine systems only. A separate CER is provided for hydrogen peroxide systems.

[5] Nonrecurring costs are the difference between a total-cost CER and the recurring estimates.

Recurring Cost

Attitude and velocity control

Independent variables	Total satellite weight or number of equivalent discretes
Functional form	Curve plotted based on engineering judgment

Total satellite weight was used in estimating costs for this subsystem.

Reaction control

Independent variables	Propellant weight
Functional form	$Y = a + bX$
R^2	0.68
Level of significance	0.1

As shown below, the results parallel the nonrecurring case for the most part. The model overestimates the cost of inexpensive systems and underestimates the cost of expensive systems. ATS-F, the most expensive system, is underestimated by $4.9 million, which when added to the $10 million underestimate of nonrecurring cost indicates clearly that the model is not well adapted for an attitude control system of that type.

	Deviations	
	Percent	Cost ($ million)
AEM	-246	-1.8
ATS-F	60	4.9
DSCS II	3	0.1
DSP II	37	1.5
MMS	-60	-1.0
S-3	-521	-1.4

ELECTRIC POWER

Nonrecurring Cost

Independent variable	End-of-lifetime solar array power
Functional form	$Y = aX^b$
R^2	0.47
Level of significance	0.01

The equation applies only to the solar array, solar cells, and batteries. The wiring harness is estimated on a cost-per-pound basis (\$3439 in 1974 dollars) as are substrates, array structure, and power regulation (\$5000). The pattern noted previously of higher-cost spacecraft being consistently underestimated does not obtain here. ATS-F is overestimated by \$4.4 million. DSCS II, which is in the data base, is overestimated by a large amount also. DSP is also in the data base, but that fact does not appear to help the DSP II estimate by much.

	Deviations	
	Percent	Cost (\$ million)
AEM	-1190	-4.4
ATS-F	-151	-4.4
DSCS II	-86	-3.1
DSP II	54	10.2
S-3	-275	-2.2

Recurring Cost

Independent variables	End-of-lifetime solar array power, spacecraft lifetime
Functional form	$Y = aX^b + cW$
R^2	0.94
Level of significance	0.01

As in the case of nonrecurring cost, wiring harnesses, array structure, etc., must be estimated separately. Also, FLEETSATCOM has

dedicated solar cells for battery charging only, a design feature lacking in the test cases where battery charging was part of the basic power requirement. The costs below do not include an allowance for dedicated solar cells.

Estimates for this subsystem are no better than those discussed previously despite greater homogeneity of equipment. The two most expensive subsystems, DSP II and MMS, are underestimated, and the other subsystems are overestimated.

	Deviations	
	Percent	Cost ($ million)
AEM	-51	-0.3
ATS-F	-88	-1.5
DSCS II	-77	-1.2
DSP II	51	2.7
MMS	45	1.7
S-3	-30	-0.1

COMMUNICATIONS

Nonrecurring Cost

Independent variables	Subsystem weight, number of transmitter chains
Functional form	$Y = a + bX + cZ$
R^2	0.44
Level of significance	>0.25

The model provides two equations: one for transmitters only and one for the entire subsystem. The latter is used here for the two communication satellites. The estimates, which include TT&C, are poor for ATS-F in both percentage and dollar terms but better for DSCS II.

	Deviations	
	Percent	Cost ($ million)
ATS-F	-146	-24.4
DSCS II	36	10.5

Recurring Cost

Independent variables	Weight, number of transmitter chains
Functional form	Y = a + bX + cZ
R^2	0.51
Level of significance	0.5

As one would hope, the FLEETSATCOM model estimates communication subsystem costs quite well. One could not have much confidence in the equation, however, on the basis of its statistical properties.

	Deviations	
	Percent	Cost ($ million)
ATS-F	8	0.7
DSCS II	13	0.8

TOTAL SPACECRAFT

The PRC model does not estimate the nonrecurring cost of any of the five test cases with acceptable accuracy. The best case, DSCS II, is most like FLEETSATCOM of any of the five, but is underestimated by 30 percent. Estimates of the two lower-cost spacecraft are off by over 100 percent and DSP II is off by 36 percent. The best recurring cost estimates are for the two communication satellites.

	Deviations			
	Nonrecurring		Recurring	
	Percent	Cost ($ million)	Percent	Cost ($ million)
AEM	-551	-12.5	-98	-2.2
ATS-F	-31	-16.9	14	2.9
DSCS II	30	17.0	-12	-1.3
DSP II	36	17.4	38	5.3
MMS	---	---	-34	-3.1
S-3	-121	-7.1	-117	-2.4

VII. SCIENCE APPLICATIONS, INCORPORATED, MODEL

It is often argued that planetary spacecraft cost more per pound than earth-orbital spacecraft because of the more stringent requirements levied upon them. Consequently, it may seem inappropriate to include a planetary cost model in this evaluation, but we were interested in finding out whether in fact the estimate would be significantly higher. The Science Applications, Inc., model was developed with the objective of forecasting future planetary mission costs within ±20 percent.[1]

In most respects it is similar to the other models discussed. Spacecraft are divided into major subsystems, and the cost of each subsystem is estimated on the basis of weight. No statistical measures are shown for the equations. The model has two unique features. First, it includes a science experiments subsystem for which, in addition to weight, the user must specify the resolution (pixels per line) of the imaging experiment.[2] Second, and more important, initial estimates are in terms of labor hours. Those hours are converted into dollars on the basis of a labor rate, and total subsystem cost is obtained by assuming that labor is a given percentage of the total. The cost of the science experiments subsystem, for example, is said to include 27.7 percent labor. Subsystem cost in that case is equal to labor cost divided by 0.277.

Forecasting man-hours is believed to have several advantages over forecasting cost directly. The most obvious is that a price-level index is needed to adjust only material costs to constant dollars; current or historical wage rates can be used for labor costs. The model does not require a material price-level index because of the labor-cost relationship mentioned above; but it does suggest a constant annual wage escalation rate for each subsystem and support area, and has built these

---

[1] L. D. Kitchen, *Manpower/Cost Estimation Model--Automated Planetary Projects*, Science Applications, Inc., Report SAI 1-120-194-C1, Rolling Meadows, Ill., March 1975.

[2] This subsystem was not included in the spacecraft model tests.

rates into all wage calculations. Using the SAI procedures results in average total escalation about 30 percent below that resulting from the Rand index shown in Sec. I. We adjusted the SAI subsystem estimates upward using the average difference in escalation to make them more comparable to the actual costs. Since the labor escalation rates differ by subsystem and support area, and the percentage of total cost for these parts is different for each spacecraft, it is unlikely that all programs would require the same adjustment. Using the same adjustment for all test cases probably contributes to the deviations shown later.

A second advantage of dealing in man-hours is said to be that the effect of learning and inheritance can be more easily analyzed. Inheritance from previous programs is considered an important input to estimates, and users must classify each subsystem as being somewhere in the range from all-new to off-the-shelf. Since the choices may strongly influence system cost, it follows that good estimates depend critically on good engineering judgment.

DATA SAMPLE

The data base for this model consists of eight planetary programs:

Mariner '64	Surveyor	Viking Lander
Mariner '69	Lunar Orbiter	Viking Orbiter
Mariner '71	Pioneer F/G	

The data sample for each CER included all eight of the above.

INHERITANCE ADJUSTMENT

The nonrecurring CERs of this model estimate the cost of designing and developing the various subsystems assuming no inheritance from previous programs. Inheritance must be accounted for explicitly by means of a gross adjustment procedure. The user chooses one of the classes below and achieves the savings indicated.

Class	Savings
Off-the-shelf	100% of nonrecurring cost
Exact repeat of subsystem	80%
Minor modification of subsystem	25%
Major modification of subsystem	5%

Choosing inheritance classes is difficult. At the subsystem level the classes are too restrictive, and at the component level the information may not be available. Consequently, we did not attempt to adjust nonrecurring costs for inheritance. The deviations shown assume no inheritance, but the percentage adjustment that would be required to reduce the deviation to zero is also given. One can then judge whether such an adjustment made a priori would have been likely or reasonable.

STRUCTURE & THERMAL

Nonrecurring Cost

Independent variables ..... Structure weight; mechanisms and landing gear weight; thermal control, pyrotechnic, and electrical cabling weight

Functional form .... $Y = aW^b + cX^d + eZ^f$

The equation overestimates nonrecurring cost for all spacecraft. Inheritance adjustments would have improved the estimates, but given the restrictive categories of inheritances, an estimator would be hard put to reduce the estimates by the percentages shown. Also, structure and thermal control subsystems are rarely able to take advantage of inheritance.

	Deviations: Percent	Deviations: Cost ($ million)	Inheritance to Give Zero Deviation
AEM	-1192	-8.2	92%
ATS-F	-161	-18.6	62%
DSCS II ...	-181	-11.1	64%
DSP II	-126	-9.8	56%
S-3	-663	-11.9	87%

Recurring Cost

Independent variable	Nonrecurring cost
Functional form	Y = aX

The inheritance adjustments do not affect the recurring cost estimates; the full nonrecurring cost is used. The results here are not much different from those obtained with other models. All of the spacecraft are overestimated. DSP II, a spacecraft that falls in between the low-cost and high-cost categories, is estimated quite well by the equation. MMS because of its relatively heavy weight is the worst outlier. Thus it appears that planetary spacecraft structure is not perceptibly different for estimating purposes from that of earth-orbital spacecraft.

	Deviations	
	Percent	Cost ($ million)
AEM	-137	-0.6
ATS-F	-29	-0.7
DSCS II	-88	-0.9
DSP II	-10	-0.2
MMS[a]	-587	-5.1
S-3	-120	-0.8

[a]Although no nonrecurring cost is shown for MMS, that cost was estimated to provide a basis for obtaining recurring cost.

TELEMETRY, TRACKING, AND COMMAND/COMMUNICATIONS

The SAI model does not distinguish between TT&C and communications. All communications equipment is considered part of the same subsystem, and that makes the model difficult to apply to communication satellites. As shown below, the model requires radio-frequency weight, data-handling subsystem weight, and antenna weight as inputs. To generate estimates for this study, two different methods were used on ATS-F and DSCS II. The first was to assume that communications equipment equates to radio-frequency equipment, TT&C equates to data-handling subsystem, and antennas are combined. The second was to estimate the communications and

TT&C separately, assuming both to be radio-frequency equipment and data-handling weight to be zero. The difference in estimates is minimal with the latter method yielding slightly better estimates.

Nonrecurring Cost

Independent variables	Radio-frequency subsystem weight; data-handling subsystem weight; antenna weight
Functional form	$Y = aW + bX^c + dZ^e$

The gross overestimates for all spacecraft in the test sample suggest that the CER is inappropriate for the communications subsystems involved. Inheritance adjustments would reduce deviations for AEM, DSP II, and S-3 somewhat, but in view of the development work required on ATS-F and DSCS II, the amount of inheritance that could be claimed would not reduce the estimates to a more reasonable number.

	Deviations		Inheritance to
	Percent	Cost ($ million)	Give Zero Deviation
		TT&C Only	
AEM	-1348	-10	93%
DSP II	-157	-16.5	61%
S-3	-563	-12.6	85%
		COMM/TT&C	
ATS-F	-942	-158	90%
DSCS II ...	-229	-67.1	70%

Recurring Cost

Independent variable	Nonrecurring cost
Functional form	$Y = aX$

This cost is overestimated in every case; both percent and dollar deviations are substantial. The results here indicate that planetary

TT&C subsystems are significantly more expensive than those in earth-orbital spacecraft in both nonrecurring and recurring costs.

	Deviations Percent	Deviations Cost ($ million)
	TT&C Only	
AEM	-267	-1.4
DSP II	-69	-2.0
MMS	-114	-3.1
S-3	-320	-2.0
	COMM/TT&C	
ATS-F	-260	-22.7
DSCS II	-209	-11.8

ATTITUDE CONTROL

Nonrecurring Cost

Independent variables ..... Subsystem weight (excluding RCS), radar weight

Functional form .... $Y = aX^b + cZ^d$

Deviations are very high in both percentages and dollars, and application of reasonable inheritance factors would not produce good estimates. The adjustments that would be required to reduce deviations to an acceptable level would not be consonant with the actual development that occurred.

The deviations include an RCS where appropriate. A separate CER, shown later, is used for that subsystem.

	Deviations Percent	Deviations Cost ($ million)	Inheritance to Give Zero Deviation
AEM	-3150	-14.3	97%
ATS-F	-162	-37.9	62%
DSCS II	-87	-15.2	47%
DSP II	-236	-26.6	70%
S-3	-926	-9.9	90%

Recurring Cost

Independent variable .... Nonrecurring cost
Functional form .... $Y = aX$

The estimates for this subsystem indicate that the CER tends to overstate cost for all types of spacecraft. It is not clear why MMS is off by such a margin, but we have seen the same anomaly with the MMS ACS turn up in some of the other models. On the basis of the current (spring 1977) GSFC estimate the subsystem is, designedly, of below-average cost.

	Deviations	
	Percent	Cost ($ million)
AEM	-184	-1.3
ATS-F	-4	-0.4
DSCS II	-77	-2.0
DSP II	-29	-1.2
MMS	-268	-4.6
S-3	-484	-1.3

RCS PROPULSION

Nonrecurring Cost

Independent variables .... Subsystem weight, terminal control system weight, aero-decelerator system weight
Functional form .... $Y = aW^b + cX^d + eZ^f$

Recurring Cost

Independent variable .... Nonrecurring cost
Functional form .... $Y = aX$

ELECTRICAL POWER

Nonrecurring Cost

Independent variable ..... Weight (excluding radioisotope thermoelectric generators)
Functional form .... Y = a + bW

All estimates of nonrecurring cost are too high, but four could be improved somewhat by adjusting for inheritance. Only the DSP II estimate would be degraded. Use of weight as an independent variable means that no distinction is made between spinning and three-axis stabilized spacecraft, but the CER appears to do a somewhat better job on the spinners.

	Deviations		Inheritance to
	Percent	Cost ($ million)	Give Zero Deviation
AEM	-2252	-8.3	96%
ATS-F	-570	-16.6	85%
DSCS II ...	-303	-10.8	75%
DSP II	-5	-0.9	5%
S-3	-832	-6.7	89%

Recurring Cost

Independent variable .... Nonrecurring cost
Functional form .... Y = aX

None of the test cases falls within the ±20 percent range SAI hoped to achieve, and for ATS-F, DSP II, and MMS the dollar deviations are large. The latter two are more expensive on a cost-per-pound basis than the CER predicts, which is especially surprising for the MMS electrical power subsystem.

	Deviations	
	Percent	Cost ($ million)
AEM	-119	-0.7
ATS-F	-73	-1.2
DSCS II	-30	-0.5
DSP II	44	2.3
MMS	34	1.3
S-3	-163	-0.7

TOTAL SPACECRAFT

Nonrecurring Cost

When the estimates for each subsystem are added together to obtain a total spacecraft cost, the total estimate exceeds the actual cost in every case by anywhere from 111 percent to 1810 percent. Inheritance adjustments would reduce those numbers considerably; however, based on what we know about the systems, only the DSP II and S-3 estimates would be reduced enough to be useful for planning. The estimates for AEM, ATS-F, and DSCS II are so high that no reasonable inheritance allowance would bring them down to a more realistic level. For the two communication satellites the problem is partially due to the lack of a communications CER and the need to estimate the cost of the communications package using the TT&C CER.

	Deviations		
	Percent	Cost ($ million)	Inheritance to Give Zero Deviation
AEM	-1810	-40.9	95%
ATS-F	-423	-231	81%
DSCS II ...	-184	-104.2	65%
DSP II	-111	-53.8	53%
S-3	-696	-41.2	87%

Recurring Cost

The results here are consistent. All spacecraft are overestimated, and only DSP II is estimated fairly well. That good performance is in part due to a cancelling-out of the various subsystem errors. Taken as

a whole, it appears that this planetary cost model overstates standard earth-orbital spacecraft recurring costs.

	Deviations	
	Percent	Cost ($ million)
AEM	-178	-4.0
ATS-F	-118	-25.0
DSCS II	-140	-15.1
DSP II	-7	-1.0
MMS	-128	-11.6
S-3	-239	-4.8

VIII. SPACE AND MISSILE SYSTEMS ORGANIZATION MODELS

The third edition of the SAMSO model is the product of about 10 years of research, development, and experience on the part of the Cost Analysis Division at SAMSO.[1] It has been in a state of continuous evolution since 1968, and has been used to make independent cost estimates of many proposed or conceptual spacecraft programs. It is probably the best-known and best-documented spacecraft model that is generally available to government and industry. An interim update, issued in January 1977, follows the same pattern as the Third Edition.[2] Spacecraft are estimated on a subsystem basis: structure, thermal control, and interstage; electrical power supply; attitude control system; telemetry, tracking, and command; and communications (mission). Alternatively, a spacecraft can be estimated on a system basis. Nonrecurring and recurring costs are estimated separately.

A unique feature of the model is that two complete sets of cost-estimating relationships are provided. The first is based on data adjusted for price-level changes and production quantity but not for differences in the state of the art. The second is based on data normalized "to account for the influences of alternate design concepts and technologies," i.e., subsystem costs of older spacecraft in the sample were reduced to make them comparable with costs incurred on more recent spacecraft when the technology was better understood or perhaps even off-the-shelf, and the subsystem costs were adjusted for differences in design complexities.

The complexity and technology-carryover factors used to normalize cost data can also be used to tailor a subsystem estimate to take into

---

[1] C. J. Rowher et al., *Space and Missile Systems Organization Unmanned Spacecraft Model*, Third Edition, USAF Space and Missile Systems Organization, Cost Analysis Division, El Segundo, Calif., August 1975.

[2] F. K. Fong et al., *Space and Missile Systems Organization Unmanned Spacecraft Cost Model--Updated Cost Estimating Relationships and Normalization Factors (An Interim Report)*, USAF Space and Missile Systems Organization, Cost Analysis Division, El Segundo, Calif., January 1977.

account certain major subsystem characteristics. In the communications subsystem, for example, complexity factors are given for the operational frequency, effective radiative power, bandwidth modulation factor, and type of amplification system. When information is available at that level of detail, more precise estimating may be possible. SAMSO recommends that the first set of CERs be used if: (1) detailed normalization information is not available; and (2) the baseline technology/ complexity of the second set of CERs is not appropriate for the system being estimated.

In this review we deemed it necessary to examine both the Third Edition and the Update because the data sample changed as described below. Also, we wanted to determine the differences in estimates that result from using both the standard and normalized procedures. In principle the latter should be more accurate, but it can be used only if detailed design data are available. Estimates for the sample of test cases do not support the hypothesis that any one set of equations will give the best answers consistently.

DATA SAMPLE

The data base for the SAMSO models has grown from 11 spacecraft in 1969 to 29 for the 1977 Update. All are earth-orbiting except for the Lunar Orbiter. Of the rest, 10 are operational sensor platforms (e.g., surveillance, weather), 12 are communications, and 6 are scientific/ experimental. The data sample used for each subsystem in the Third Edition model is shown in Table 8. The sample is the same for both the standard and normalized models except for three instances where one spacecraft was added to the normalized model's data base:

TT&C (recurring cost)	ATS-A (M/G)
EPS (nonrecurring cost)	Vela
COMM/TTC (nonrecurring)	INTELSAT III

These additions were possible because of the homogeneity achieved by normalizing the data.

Table 8

CER DATA SAMPLE FOR SAMSO MODEL (THIRD EDITION)

Spacecraft	Structure, Thermal, Interstage NR	Structure, Thermal, Interstage R	Telemetry, Tracking, & Command NR	Telemetry, Tracking, & Command R	Attitude Control Subsystem NR	Attitude Control Subsystem R	Electrical Power Subsystem NR	Electrical Power Subsystem R	Combined Communi-cations and TT&C NR	Combined Communi-cations and TT&C R	Program Level Costs NR	Program Level Costs R
Vela	x	x	x	x	x	x		Synch			x	x
VASP	x	x	x	x	x	x	Body	Synch			x	x
IDCSP	x	x			x	x	Body	Synch	x	x	x	x
IDCSP/A	x	x			x	x	Body	Synch	x	x	x	x
TACSAT	x	x					Body		x	x	x	x
SYNCOM	x	x			x	x	Body	Synch	x	x	x	x
Lunar Orbiter	x	x		x		x		Synch			x	
ATS A (M/G)	x	x				x		Sub		x	x	x
ATS B,C (S/S)	x	x			x	x		Synch	x	x	x	x
ATS D,E (S/G)	x	x				x		Synch	x	x	x	x
INTELSAT III	x	x			x	x	Body	Synch		x	x	x
DSP I	x	x	x	x	x	x	Body					x
TIROS M	x	x	x	x	x	x	Paddle	Sub			x	x
DSCS II	x	x			x	x	Body	Synch	x	x	x	x
SMS	x	x	x	x	x	x	Body	Synch			x	x
NIMBUS E,F		x		x		x	Paddle	Sub			x	x
ERTS A,B		x	x	x		x	Paddle	Sub			x	x
DSP II		x		x		x						x
DMSP 5D	x	x	x	x	x	x		Sub			x	x
P72-2		x		x		x	Paddle	Sub			x	x
S-3		x		x		x	Paddle	Sub			x	x
OSO I		x	x	x		x	Paddle	Sub			x	x
ATS-F	x	x			x	x	Paddle	Synch	x	x	x	x
Atmo. exp.		x	x	x		x	Paddle	Sub			x	x
INTELSAT IV	x	x			x	x	Body	Synch	x	x	x	x

Data samples are the same for both the standard and normalized models in the 1977 Update, but they are slightly different from those in the Third Edition. A number of spacecraft were deleted from the data base for some subsystems on the grounds of short design life ($\leq$ 12 months), technical complexity, or extreme low-cost philosophy. Others were added because of new data or new sample definition. The changes are shown in Table 9.

Table 9

CER DATA SAMPLE CHANGES FROM SAMSO III STANDARD TO SAMSO III UPDATE

Structure, Thermal, Interstage	Telemetry, Tracking, & Command	Attitude Control Subsystem	Electrical Power Subsystem	Combined Communications and TT&C	Program-Level Costs
			Nonrecurring		
- Lunar Orbiter[a] - Vela[a] - TIROS M[a] + NATO III	- Vela[a] - SMS[b] + NIMBUS E,F	- Vela[a] - TIROS M[a] + ATS A (M/G) + ATS D,E (S/G) + NATO III	Body to spin - IDCSP + ATS B,C (S/S) + OSO I + NATO III Paddle to 3-axis - P72-2[a] - S-3[a] - OSO I + ATS A (M/G) + ATS D,E (S/G)	+ ATS A (M/G) + NATO III + INTELSAT III	+ NATO III
			Recurring		
+ NATO III	- Atmospheric Explorer[c]	- Atmospheric Explorer[c] + NATO III	Synchronous + - VASP - IDCSP + TACSAT + NATO III Subsynchronous - DMSP 5D + IDCSP	+ NATO III	- DSP I[d] - DSP II[d] + Lunar Orbiter + NATO III

[a]Eliminated because design life ≤ 12 months.

[b]Eliminated for excessive technological complexity.

[c]Eliminated for extreme low-cost philosophy.

[d]Payload integration costs could not be identified and deleted.

STRUCTURE, THERMAL CONTROL, AND INTERSTAGE (STI)

Nonrecurring Cost

	Third Edition		1977 Update	
	Standard	Normalized	Standard	Normalized
Independent variable ...	Weight	Same	Weight	Same
Functional form	$Y = a+bX^c$	Same	$Y = a+bX^c$	Same
R^2	0.63	0.77	0.65	0.69
Level of significance ..	0.01	0.01	0.01	0.01

From the pattern of deviations shown below, it is clear that none of the four models is well adapted to low-cost spacecraft, but the normalized 1977 Update is marginally better than the others. It is best on all the other spacecraft except DSP II, for which Third Edition is slightly better. For this cost element the normalized 1977 Update appears preferable.

Deviations

	Third Edition				1977 Update			
	Standard		Normalized		Standard		Normalized	
	%	$	%	$	%	$	%	$
AEM	-429	-3.0	-319	-2.2	-330	-2.3	-282	-1.9
ATS-F	-7	-0.9	-7	-0.8	-6	0.7	1	0.1
DSCS II	-32	-2.0	-21	-1.3	-20	-1.3	-16	-1.0
DSP II	-1	0.0	10	0.8	9	0.7	18	1.4
S-3	-223	-4.0	-165	-3.0	-178	-3.2	-145	-2.6

Recurring Cost

	Third Edition		1977 Update	
	Standard	Normalized	Standard	Normalized
Independent variable ...	Weight	Same	Weight	Same
Functional form	$Y = a+bX^c$	Same	$Y = a+bX^c$	Same
R^2	0.78	0.81	0.65	0.69
Level of significance ..	0.01	0.01	0.01	0.01

The deviations below show how similar are the estimates obtained from the four models. Only in the case of the MMS are the differences substantial; three estimates there are off by over 100 percent, presumably because structure on the MMS is heavy but inexpensive. The AEM is actually underestimated, and estimates for both small spacecraft are good.

Deviations

	Third Edition				1977 Update			
	Standard		Normalized		Standard		Normalized	
	%	$	%	$	%	$	%	$
AEM	34	0.1	38	0.2	33	0.1	43	0.2
ATS-F	-10	-0.3	-12	-0.3	2	0.1	8	0.2
DSCS II	-42	-0.4	-38	-0.4	-25	-0.2	-30	-0.3
DSP II	23	0.4	28	0.5	32	0.6	38	0.6
MMS	-131	-1.1	-209	-1.8	-112	-1.0	-84	-0.7
S-3	-14	-0.1	-1	0.0	-2	0.0	9	0.1

TELEMETRY, TRACKING & COMMAND (TT&C)

Nonrecurring Cost

	Third Edition		1977 Update	
	Standard	Normalized	Standard	Normalized
Independent variable ...	Weight	Same	Weight	Same
Functional form	Y = a+bX	Same	Y = a+bX	Same
R^2	0.67	0.65	0.54	0.59
Level of significance ..	0.01	0.01	0.05	0.05

In the sequence of models shown above, each revision results in a lower a-value while b remains about the same. The effect is to achieve better estimates of the low-weight TT&C subsystems in our test sample with each revision, but at the same time to degrade the DSP II estimate. The trend toward lower nonrecurring costs for TT&C that is illustrated by the progression of models seems reasonable in view of the amount of off-the-shelf equipment now available.

Deviations

	Third Edition				1977 Update			
	Standard		Normalized		Standard		Normalized	
	%	$	%	$	%	$	%	$
AEM	-368	-2.7	-159	-1.2	-120	-0.9	-80	-0.6
DSP II	47	4.9	57	5.9	63	6.6	64	6.7
S-3	-86	-1.9	-39	-0.9	-5	-0.1	10	0.2

Recurring Cost

	Third Edition		1977 Update	
	Standard	Normalized	Standard	Normalized
Independent variable ...	Weight	Same	Weight	Same
Functional form	Y = a+bX	Same	Y = a+bX	Same
R^2	0.75	0.71	0.73	0.72
Level of significance ..	0.01	0.01	0.01	0.01

MMS is the outlier here because of its weight, 161 lb, and because the CER is linear. Virtually no reduction in cost per pound occurs after a weight of 100 lb has been reached, which implies that the functional form may be wrong for subsystems as heavy as that of the MMS.

In both editions the effect of normalization is to reduce the estimates for all four test cases. Thus the normalized equations give better estimates for low-cost systems and worse estimates for high-cost systems.

Deviations

	Third Edition				1977 Update			
	Standard		Normalized		Standard		Normalized	
	%	$	%	$	%	$	%	$
AEM	-40	-0.2	-17	-0.1	-50	-0.3	-26	-0.1
DSP II	26	0.7	30	0.9	27	0.8	31	0.9
MMS	-51	-1.4	-42	-1.2	-45	-1.2	-27	-0.7
S-3	-86	-0.5	-76	-0.5	-90	-0.6	-66	-0.4

ATTITUDE CONTROL

The attitude control subsystem includes reaction control hardware used for spinup and/or despin, stationkeeping, and satellite orientation.

Nonrecurring Cost

	Third Edition		1977 Update	
	Standard	Normalized	Standard	Normalized
Independent variable ...	Weight	Same	Weight	Same
Functional form	$Y = aX^b$	Same	$Y = a+bX^c$	Same
R^2	0.78	0.76	0.80	0.78
Level of significance ..	0.01	0.01	0.01	0.01

With nonrecurring cost estimated as a function of weight, the deviations follow a consistent pattern in all four models: Low-weight systems are severely overestimated, DSP II is slightly overestimated, and the communication satellites are slightly underestimated. The complexity of the ACS (i.e., despun platform, three-axis, and spinner) appear to correlate to the error. The 1977 Update improves the quality of the ATS-F and DSCS II estimates, but other estimates suffer.

Deviations

	Third Edition				1977 Update			
	Standard		Normalized		Standard		Normalized	
	%	$	%	$	%	$	%	$
AEM	-1128	-5.1	-935	-4.2	-1136	-5.2	-986	-4.5
ATS-F	29	6.8	16	3.8	5	1.2	2	0.4
DSCS II ...	34	6.0	37	6.5	21	3.7	24	4.2
DSP II	-18	-2.0	-15	-1.7	-47	-5.3	-46	-5.1
S-3	-334	-3.6	-238	-2.6	-323	-3.5	-275	-3.0

Recurring Cost

	Third Edition		1977 Update	
	Standard	Normalized	Standard	Normalized
Independent variable ...	Weight	Same	Weight	Same
Functional form	$Y = aX^b$	Same	$Y = a+bX^c$	Same
R^2	0.75	0.77	0.74	0.75
Level of significance ..	0.01	0.01	0.01	0.01

The largest percentage deviations are for the two spacecraft that lack a reaction-control system: MMS and S-3. That may suggest the desirability of estimating the RCS separately from the ACS. The Third Edition provides better estimates than the Update for four of the six test cases. Only ATS-F and DSP II benefit from the addition of a constant to the estimating equation, and that constant virtually ensures that all lower-cost systems will be overestimated.

Deviations

	Third Edition				1977 Update			
	Standard		Normalized		Standard		Normalized	
	%	$	%	$	%	$	%	$
AEM	-11	-0.1	6	0	-72	-0.5	-56	-0.4
ATS-F	41	3.4	39	3.2	23	1.9	21	1.8
DSCS II	-3	-0.1	0	0.0	-43	-1.1	-45	-1.2
DSP II	18	0.8	21	0.9	-11	-0.4	-10	-0.4
MMS	-123	-2.1	-122	-2.1	-198	-3.4	-190	-3.3
S-3	-133	-0.3	-86	-0.2	-269	-0.7	-235	-0.6

ELECTRICAL POWER SUPPLY (EPS)

Nonrecurring Cost

	Third Edition			
	Body-mounted Arrays		Paddle-mounted Arrays	
	Standard	Normalized	Standard	Normalized
Independent variables ...	Max. array output	Same	Max. array output	Same
Functional form	$Y = aX^b$	Same	$Y = a+bX$	Same
R^2	0.80	0.81	0.78	0.77
Level of significance ...	0.01	0.01	0.01	0.01

	1977 Update			
	Spin-stabilized Spacecraft		Three-axis Stabilized	
	Standard	Normalized	Standard	Normalized
Independent variables ...	Weight, max. array output	Same	Max. array output	Same
Functional form	$Y = a+bX$	Same	$Y = a+bX$	Same
R^2	0.67	0.67	0.72	0.75
Level of significance ...	0.01	0.01	0.05	0.05

The Third Edition distinguishes between body-mounted and paddle-mounted solar arrays, which means that the DSCS II and DSP II are estimated with one set of CERs while another set is used for the other three tests. The 1977 Update, on the other hand, segregates spin-stabilized and three-axis spacecraft, isolating AEM and ATS-F from the rest of the test cases. The change does not affect ATS-F estimates, but deviations on other spacecraft change appreciably. AEM and S-3 are adversely affected while DSCS II and DSP II improve.

Deviations

	Third Edition				1977 Update			
	Standard		Normalized		Standard		Normalized	
	%	$	%	$	%	$	%	$
AEM	-207	-0.8	-195	-0.7	-336	-1.2	-273	[illegible]
ATS-F	2	0.1	2	0.1	0	0	2	0.1
DSCS II	-121	-4.3	-128	-4.5	-89	-3.2	-84	[illegible]
DSP II	48	9.0	45	8.6	25	4.7	27	[illegible]
S-3	32	0.3	31	0.3	-238	-1.9	-196	[illegible]

Recurring Cost

Synchronous Altitude and Above

	Third Edition		1977 Update	
	Standard	Normalized	Standard	Normalized
Independent variables ...	Max. array output	Same	Weight, BOL power	Same
Functional form	$Y = aX^b$	Same	$Y = aX^b$	Same
R^2	0.81	0.82	0.66	[illegible]
Level of significance ...	0.01	0.01	0.01	[illegible]

Less Than Synchronous Altitude

	Third Edition		1977 Update	
	Standard	Normalized	Standard	Normalized
Independent variable	Weight	Same	Weight	Same
Functional form	$Y = a+bX$	Same	$Y = aX^b$	Same
R^2	0.77	0.78	0.79	[illegible]
Level of significance ...	0.01	0.01	0.01	[illegible]

The pattern of deviations for the Third Edition is essentially the same for both the standard and normalized versions, and in dollar terms all are reasonably good. With the 1977 Update five estimates are improved while one is degraded: DSP II is the outlier. The normalized version is marginally preferable to the standard, but the difference is slight.

Deviations

	Third Edition				1977 Update			
	Standard		Normalized		Standard		Normalized	
	%	$	%	$	%	$	%	$
AEM	82	0.5	82	0.5	9	0.1	16	0.1
ATS-F	-96	-1.6	-95	-1.6	-54	-0.9	-47	-0.8
DSCS II	-82	-1.3	-76	-1.2	-34	-0.6	-32	-0.5
DSP II	22	1.2	22	1.1	48	2.6	47	2.5
MMS	-28	-1.0	-22	-0.8	4	0.1	18	0.7
S-3	81	0.4	81	0.4	-18	-0.1	1	0

COMMUNICATIONS/TT&C

For communication satellites, TT&C and communication costs can be estimated separately or as a package. The CERs discussed here are for the combined cost of TT&C and communications.

Nonrecurring Cost

	Third Edition		1977 Update	
	Standard	Normalized	Standard	Normalized
Independent variable ...	Max. array output	Same	Weight	Same
Functional form	$Y = a+bX^c$	Same	$Y = a+bX^c$	Same
R^2	0.88	0.85	0.75	0.74
Level of significance ..	0.01	0.01	0.01	0.01

The change in independent variables from maximum array output to subsystem weight increases the divergence between ATS-F and DSCS II estimates, because while their powers are roughly comparable, the ATS-F subsystem weighs over twice as much as that of DSCS II. The Third Edition does better, as shown below, but with large deviations.

Deviations

	Third Edition				1977 Update			
	Standard		Normalized		Standard		Normalized	
	%	$	%	$	%	$	%	$
ATS-F	-33	-5.5	-30	-5.0	-61	-10.1	-59	-9.8
DSCS II	32	9.3	34	10.1	38	11.0	40	11.7

Recurring Cost

	Third Edition		1977 Update	
	Standard	Normalized	Standard	Normalized
Independent variables ...	Weight, max. array output	Same	Weight	Same
Functional form	Y = a+bX	Same	$Y = a+bX^c$	Same
R^2	0.88	0.89	0.83	0.81
Level of significance ...	0.01	0.01	0.01	0.01

All four models overestimate both test cases. The normalized versions appear to be slightly better for both test cases, but changing independent variables and functional form has little effect on the estimates.

Deviations

	Third Edition				1977 Update			
	Standard		Normalized		Standard		Normalized	
	%	$	%	$	%	$	%	$
ATS-F	-60	-5.2	-56	-4.9	-49	-4.3	-50	-4.4
DSCS II	-31	-1.8	-27	-1.6	-38	-2.2	-33	-1.9

TOTAL COST

The SAMSO standard models include a provision for estimating "platform" cost, i.e., total cost without payload, where a quick estimate is needed or where information needed for a detailed estimate is lacking.

Nonrecurring Cost

	Third Edition	1977 Update
Independent variable	Platform weight	Platform weight
Functional form	$Y = a+bX^c$	$Y = aX^b$
R^2	0.59	0.86
Level of significance ...	0.01	0.01

When the results of using the platform CERs are compared with the summations of subsystem cost estimates, no one model stands out as consistently best or worst. In percentage terms the three large spacecraft are estimated fairly well, while the two small spacecraft are greatly overestimated. Thus one could not rely on any of the SAMSO models for estimates of nonrecurring costs for low-cost satellites such as AEM and S-3.

	Standard		Normalized		Platform	
	%	$	%	$	%	$
Third Edition						
AEM	-513	-11.6	-370	-8.3	-733	-16.9
ATS-F	1	0.5	-3	-1.9	-33	-12.6
DSCS II ..	16	9.0	19	10.8	35	19.6
DSP II ...	25	11.9	28	13.7	23	11.2
S-3	-157	-9.3	-104	-6.1	-266	-15.7
1977 Update						
AEM	-423	-9.6	-355	-8.0	-549	-12.6
ATS-F	-18	-9.7	-17	-9.3	-6	-2.4
DSCS II ..	18	10.3	21	11.9	-6	-1.6
DSP II ...	14	6.6	17	8.1	34	16.3
S-3	-147	-8.7	-117	-6.9	-209	-12.3

Recurring Cost

	Third Edition	1977 Update
Independent variable	Platform weight	Platform weight
Functional form	$Y = a+bX$	$Y = a+bX$
R^2	0.83	0.72
Level of significance ...	0.01	0.01

The platform CER provides the best estimate of DSCS II and DSP II, but overestimates all other spacecraft and is particularly high on the two largest, ATS-F and MMS. No one model is consistently better than the others. Increased accuracy for one estimate is offset by decreased accuracy for another. The 1977 Update: Normalized appears to give the best overall results, and lacking other guidance one would have to choose it over the others.

Deviations

	Standard		Normalized		Platform	
	%	$	%	$	%	$
Third Edition						
AEM	15	0.3	26	0.6	-41	-1.0
ATS-F	-17	-3.7	-17	-3.6	-80	-10.1
DSCS II ..	-33	-3.6	-29	-3.2	-28	-3.0
DSP II ...	22	3.1	24	3.4	1	0.1
MMS	-63	-5.7	-65	-5.9	-98	-8.9
S-3	-32	-0.6	-18	-0.4	-128	-2.6
1977 Update						
AEM	-26	-0.6	-12	-0.3	-18	-0.4
ATS-F	-15	-3.2	-15	-3.2	-47	-5.9
DSCS II ..	-37	-4.1	-36	-3.9	-75	-3.9
DSP II ...	25	3.5	26	3.6	19	2.6
MMS	-61	-5.5	-45	-4.1	-62	-5.6
S-3	-67	-1.4	-48	-1.0	-88	-1.8

IX. COMPARISONS

Comparisons among models can be misleading because the models are designed for different purposes. The GSFC model is intended only for GSFC programs, the PRC model for FLEETSATCOM only, the SAI model for planetary missions, etc. Yet comparisons can be useful. In this section we compare model results to determine which models or portions of models may be applicable to future Air Force spacecraft and also which estimating procedures seem most useful.

TOTAL-COST VERSUS SUBSYSTEM-COST MODELS

The models reviewed above are of two general types: those that estimate each subsystem separately and sum the estimates to obtain a total spacecraft cost, and those that estimate total spacecraft cost directly. Comparisons between the two are inevitable and legitimate, because for many purposes only a total-spacecraft estimate is required. A question frequently asked concerns the accuracy of total-cost estimates versus estimates built up by subsystem. Table 10 compares the dollar deviations for four total-cost models with those of seven subsystem-cost models. GSFC and SAI are not included in the comparison of nonrecurring costs because both models require judgmental inputs that we did not feel qualified to provide.

Table 10 suggests that the choice is not between total-cost and subsystem-cost models. None of the nine models listed provides a usable estimate (i.e., having a deviation of less than 25 percent) of nonrecurring cost for the AEM, DSP II, or S-3. The SAMSO Update total-cost model gives the best estimate on DSCS II and a good estimate on ATS-F. Thus we cannot rule out the utility of total-cost models for estimating nonrecurring costs. All models indicate their inapplicability to low-cost spacecraft by overestimates of 100 to 700 percent on AEM and S-3. For typical spacecraft except DSCS II, the SAMSO models are consistently better than the mean, and the Third Edition, in both its standard and normalized versions, is very close to the actual ATS-F nonrecurring cost. The NASA HQ model, on the other hand,

Table 10

DEVIATIONS IN ESTIMATES OF TOTAL COST

(In million $ 1976)

Model	AEM	ATS-F	DSCS II	DSP II	MMS	S-3
Nonrecurring						
Total-cost models						
Aerospace	-11.6	-22.6	6.3	16.4		-13.8
SAMSO 3d Ed.	-16.9	-12.6	19.6	11.2		-15.7
SAMSO Update	-12.6	-2.4	-1.6	16.3		-12.3
Subsystem-cost models						
PRC	-12.5	-16.9	17.0	17.4		-7.1
NASA HQ	-9.6	-70.7	3.6	10.7		-10.1
SAMSO 3d Ed.						
Standard	-11.6	0.5	9.0	11.9		-9.3
Normalized	-8.3	-1.9	10.8	13.7		-6.1
SAMSO Update						
Standard	-9.6	-9.7	10.3	6.6		-8.7
Normalized	-8.0	-9.3	11.9	8.1		-6.9
Absolute mean	11.2	16.3	10.1	12.5		10.0
Actual cost	2.3	54.6	56.6	48.4		5.9
Recurring						
Total-cost models						
Aerospace	-0.6	-18.4	-5.0	-2.4	-12.4	-2.5
GSFC: D(4)	-4.1	14.9	-12.5	-6.6	-16.5	-6.7
SAMSO 3d Ed.	-1.0	-10.1	-3.0	0.1	-8.9	-2.6
SAMSO Update	-0.4	-5.9	-3.9	2.6	-5.6	-1.8
Subsystem-cost models						
PRC	-2.2	2.9	-1.3	5.3	-3.1	-2.4
SAI	-4	-25.0	-15.1	-1	-11.6	-4.8
NASA HQ	-0.9	2.8	-5.6	0.5	-3.5	-0.9
SAMSO 3d Ed.						
Standard	0.3	-3.7	-3.6	3.1	-5.7	-0.6
Normalized	0.6	-3.6	-3.2	3.4	-5.9	-0.4
SAMSO Update						
Standard	-0.6	-3.2	-4.1	3.5	-5.5	-1.4
Normalized	-0.3	-3.2	-3.9	3.6	-4.1	-1
Absolute mean	1.4	8.6	5.6	3.0	7.5	2.3
Actual cost	2.3	21.3	10.8	14.0	9.0	2.0

overestimates that cost by about $70 million because of the complexity level chosen. The results suggest that no model can be used mechanically without some knowledge of the special characteristics of each spacecraft program. For typical programs the SAMSO standard models, which require a minimum of information, appear to give estimates that are at least as good as those of other models. For unusual programs, outputs of all the models reviewed required adjustment.

SAMSO Update total-cost model deviations are lower than the mean for recurring cost in every case, and in some instances they are lower than those of the subsystem-cost models. Aerospace deviations are lower than the mean for two of the six spacecraft; but since GSFC deviations are very high, one cannot generalize about the merit of total-cost estimates on the basis of that comparison. Generally, we conclude that total-cost models can be useful and deserve more attention than they have received in the past. The utility of planetary spacecraft models for estimating earth-orbital spacecraft costs appears questionable based on the SAI performance.

STRUCTURE, THERMAL CONTROL, AND INTERSTAGE

All models use weight as the basic independent variable for estimating the cost of structure, thermal control, and interstage. NASA HQ includes a complexity factor as well. SAI includes an inheritance factor for nonrecurring cost and has separate estimating relationships for different categories of weight, i.e., structure subsystem; mechanisms and landing gear; and thermal control, pyrotechnic and electrical cabling components. The other models lump all weight of that kind into a single category and use an equation either of the type $Y = aX^b$ or $Y = a + bX^c$.

The results, as seen in Table 11 consistently favor the recurring-cost estimate. The special features of the SAI and NASA HQ models are reflected to a degree in these results. The complexity level assigned by the NASA HQ model to ATS-F structure causes the nonrecurring-cost estimate to be almost $9 million too high, and the SAI recurring-cost estimate of MMS structure is about $5 million too high. All models overestimate the nonrecurring cost of S-3 substantially, but the PRC and NASA HQ equations provide good estimates of the AEM. The

Table 11

DEVIATIONS IN ESTIMATES OF STRUCTURE, THERMAL CONTROL, AND INTERSTAGE COST

(In million $ 1976)

Model	AEM	ATS-F	DSCS II	DSP II	MMS	S-3
			Nonrecurring			
PRC	-1	1.9	0.6	2.4		-1.7
NASA HQ	-0.6	-8.9	-1.6	1.1		-2.4
SAMSO 3d Ed.						
Standard	-3.0	-0.9	-2.0	0		-4.0
Normalized	-2.2	-0.8	-1.3	0.8		-3.0
SAMSO Update						
Standard	-2.3	0.7	-1.3	0.7		-3.2
Normalized	-1.9	0.1	-1.0	1.4		-2.6
Absolute mean	1.8	2.2	1.3	1.1		2.8
Actual cost	0.7	11.5	6.2	7.8		1.8
			Recurring			
PRC	0	-1.3	-1.0	-0.1	-3.0	-0.4
SAI	-0.6	-0.7	-0.9	-0.2	-5.1	-0.8
NASA HQ	-0.3	-2.7	0.1	0.7	1.5	0
SAMSO 3d Ed.						
Standard	0.1	-0.3	-0.4	0.4	-1.1	-0.1
Normalized	0.2	-0.3	-0.4	0.5	-1.8	0
SAMSO Update						
Standard	0.1	0.1	-0.2	0.6	-1.0	0
Normalized	0.2	0.2	-0.3	0.6	-0.7	0.1
Absolute mean	0.2	0.8	0.5	0.4	2.0	0.2
Actual cost	0.4	2.6	1.0	1.7	0.9	0.7

Y-intercept in the other equations appears to be inappropriate for low-cost satellites.

With the exceptions noted above, estimates of structure, thermal control, and interstage are generally well within the error-limits acceptable for spacecraft.

TELEMETRY, TRACKING, AND COMMAND

The TT&C subsystem has a single independent variable in most models--weight--but there are a few variations on that theme. As

shown by Table 12, the best estimates of nonrecurring cost are provided by the PRC model, which includes the number of commands as a second explanatory variable. The NASA HQ levels of complexity are not designed for spacecraft such as AEM and S-3, so when they are combined with weight they vastly overstate nonrecurring cost for that pair. On the other hand, they contribute to a very good estimate of the DSP TT&C. SAMSO prefers the functional form Y = a + bX; for nonrecurring cost, that has the effect of overestimating the smaller TT&C subsystem and underestimating the heavier ones. The PRC curve ($Y = aW^bX^c$) fits the test cases better.

Table 12

DEVIATIONS IN ESTIMATES OF TT&C COST

(In million $ 1976)

Model	AEM	DSP II	MMS	S-3
Nonrecurring				
PRC	0.1	3.0		0.4
NASA HQ	-3.2	1.8		-3.3
SAMSO 3d Ed.				
Standard	-2.7	4.9		-1.9
Normalized	-1.2	5.9		-0.9
SAMSO Update				
Standard	-0.9	6.6		-0.1
Normalized	-0.6	6.7		0.2
Absolute mean	1.5	4.9		1.2
Actual cost	0.7	10.5		2.2
Recurring				
PRC	-0.1	1.2	-0.7	-0.5
SAI	-1.4	-2.0	-3.1	-2.0
NASA HQ	-0.4	1.1	0.5	-0.7
SAMSO 3d Ed.				
Standard	-0.2	0.7	-1.4	-0.5
Normalized	-0.1	0.9	-1.2	-0.5
SAMSO Update				
Standard	-0.3	0.8	-1.2	-0.6
Normalized	-0.1	0.9	-0.7	-0.4
Absolute mean	0.4	1.1	1.3	0.7
Actual cost	0.5	2.9	2.7	0.6

Estimates of recurring cost are fairly good for all models except SAI, which overestimates TT&C cost on all test cases but is particularly bad on low-cost spacecraft. SAI differs from the other models in that radio-frequency equipment weight, data-handling weight, and antenna weight are treated as separate variables. A more likely reason for the higher estimate, however, is that the model is intended to be used for planetary spacecraft.

ATTITUDE CONTROL

In the attitude control subsystem, weight again is the dominant independent variable for both nonrecurring and recurring cost, but PRC uses total spacecraft weight rather than subsystem weight. PRC and NASA HQ estimate the cost of reaction control separately, PRC as a function of propellant weight and pointing accuracy, NASA HQ as a function of thrust. Both GRC and PRC distinguish between three-axis and spin-stabilized spacecraft. Despite those differences none of the models estimates the AEM and S-3 *nonrecurring cost* with less than 200 percent deviation. The SAMSO normalized models, which have a single independent variable--total subsystem weight including reaction control--and treat all types of stabilization the same, provide the best nonrecurring cost-estimates on the two small spacecraft (Table 13), but they are not good enough to be usable. The pattern of deviations is such that no single estimating procedure stands out, but the simple SAMSO approach appears to avoid gross errors better than do the more judgmental models.

For recurring cost, SAMSO models produce the lowest deviations on most spacecraft. GRC is decidedly superior on MMS, perhaps because MMS has no reaction control system. SAI makes a very good estimate on ATS-F with subsystem weight as the only explanatory variable; thus it appears that variables other than weight do not contribute perceptibly to improved estimates.

ELECTRICAL POWER

All estimates of nonrecurring cost are based on either weight or maximum array output (either BOL or EOL) or a combination of the two, i.e., the product of weight and power. In addition there is a consensus

Table 13

DEVIATIONS IN ESTIMATES OF ATTITUDE CONTROL COST

(In million $ 1976)

Model	AEM	ATS-F	DSCS II	DSP II	MMS	S-3
			Nonrecurring			
GRC	-14.7		5.8			-4.7
PRC	-7.1	10.0	9.1	1.8		-3.6
NASA HQ	-3.2	-27.7	8.6	-7.4		-2.1
SAMSO 3d Ed.						
Standard	-5.1	6.8	6.0	-2.0		-3.6
Normalized	-4.2	3.8	6.5	-1.7		-2.6
SAMSO Update						
Standard	-5.2	1.2	3.7	-5.3		-3.5
Normalized	-4.5	0.4	4.2	-5.1		-3.0
Absolute mean	6.3	8.3	6.3	3.9		3.3
Actual cost	0.5	23.4	17.5	11.2		1.1
			Recurring			
GRC	-0.1		1.5		0.4	-0.4
PRC	-1.8	4.9	0.1	1.5	-1.0	-1.4
SAI	-1.3	-0.4	-2.0	-1.2	-4.6	-1.3
NASA HQ	0.1	-3.8	-1.6	-2.7	-4.7	-0.2
SAMSO 3d Ed.						
Standard	-0.1	3.4	-0.1	0.8	-2.1	-0.3
Normalized	0	3.2	0.0	0.9	-2.1	-0.2
SAMSO Update						
Standard	-0.5	1.9	-1.1	-0.4	-3.4	-0.7
Normalized	-0.4	1.8	-1.2	0.4	-3.3	-0.6
Absolute mean	0.5	2.8	0.7	1.1	2.7	0.6
Actual cost	0.7	8.3	2.6	4.1	1.7	0.3

that spacecraft should be categorized either by type of stabilization (three-axis versus spin) or by type of array (body-mounted versus paddle-mounted), and that the appropriate functional form is Y = a + bX. For most of the spacecraft in the test sample it does not appear that it makes much difference which of the alternatives above are selected. As shown in Table 14, nonrecurring-cost estimates from the SAMSO Third Edition--both standard and normalized--are the most reliable for AEM and S-3, probably because the S-3 and P72-2 were in the data base from

Table 14

DEVIATIONS IN ESTIMATES OF ELECTRICAL POWER COSTS

(In million $ 1976)

Model	AEM	ATS-F	DSCS II	DSP II	MMS	S-3
Nonrecurring						
PRC	-4.4	-4.4	-3.1	10.2		-2.2
NASA HQ	-2.6	-0.8	-0.4	15.2		-2.3
SAMSO 3d Ed.						
Standard	-0.8	0.1	-4.3	9.0		0.3
Normalized	-0.7	0.1	-4.5	8.6		0.3
SAMSO Update						
Standard	-1.2	0	-3.2	4.7		-1.9
Normalized	-1.0	0.1	-3.0	5.1		-1.6
Absolute mean	1.8	0.9	3.1	8.8		1.4
Actual cost	0.4	2.9	3.6	18.9		0.8
Recurring						
PRC	-0.3	-1.5	-1.2	2.7	1.7	-0.1
SAI	-0.7	-1.2	-0.5	2.3	1.3	-0.7
NASA HQ	-0.3	-0.2	-1.2	1.3	2.2	0
SAMSO 3d Ed.						
Standard	0.5	-1.6	-1.3	1.2	-1.0	0.4
Normalized	0.5	-1.6	-1.2	1.1	-0.8	0.4
SAMSO Update						
Standard	0.1	-0.9	-0.6	2.6	0.1	-0.1
Normalized	0.1	-0.8	-0.5	2.5	0.7	0
Absolute mean	0.4	1.1	0.9	2.0	1.1	0.2
Actual cost	0.6	1.7	1.6	5.3	3.7	0.4

which the CER was derived. The SAMSO Update estimates are generally higher than those of the Third Edition, but whether that is due to the incorporation of a weight variable or a change in the data base is not clear.

The various models differ in the way they estimate recurring costs; but since all are reasonably accurate on at least two of the test spacecraft, it is difficult to infer a preferred procedure. SAMSO separates synchronous-altitude from lower-altitude spacecraft, and estimates the latter quite well using subsystem weight as the only

explanatory variable. NASA HQ and the normalized SAMSO Update provide precise estimates (zero deviation) of the S-3 electrical power subsystem, the former having maximum array output as the primary independent variable, the latter having weight. The SAMSO Update provides good estimates on five of the six spacecraft, but it should be noted that all estimates of this subsystem are reasonably good except for DSP II. One must conclude that electrical power subsystems are sufficiently homogeneous, and both power and weight correlate sufficiently well with cost, that any properly constructed model should generate acceptable estimates.

COMMUNICATIONS AND TT&C

Only the two communication satellites, ATS-F and DSCS II, have a combined TT&C and communication subsystem, and only the PRC and SAMSO models provide specifically for that type of subsystem. On the basis of such a small sample no positive statement about the models is warranted. The SAMSO Third Edition provides the best estimates of nonrecurring cost (Table 15), and the only independent variable is maximum array output. Actually, on DSCS II most of the estimates are about the same regardless of explanatory variable or functional form. Only the NASA HQ model differs greatly and that is because of a complexity factor. On ATS-F use of weight or weight and transmitter chains results in a substantial overstatement of cost.

The PRC model is generally best for recurring-cost estimates. All SAMSO estimates are comparable despite differences between the Third Edition and the Update in variables, functional form, and data base. SAI is clearly not intended for communication satellites. Assuming that the basic data are correct, we must conclude that neither weight alone nor weight and power together adequately explain TT&C/Communications cost. The combination of weight and number of transmitter chains shows the most promise.

Table 15

DEVIATIONS IN ESTIMATES OF TT&C/
COMMUNICATIONS COST

(In million $ 1976)

Model	ATS-F	DSCS II
Nonrecurring		
PRC	-24.4	10.5
NASA HQ	-33.3	-3.0
SAMSO 3d Ed.		
Standard	-5.5	9.3
Normalized	-5.0	10.1
SAMSO Update		
Standard	-10.1	11.0
Normalized	-9.8	11.7
Absolute mean	14.7	9.3
Actual cost	16.7	8.7
Recurring		
PRC	0.7	0.8
SAI	-22.7	-11.8
NASA HQ	1.9	-2.9
SAMSO 3d Ed.		
Standard	-5.2	-1.8
Normalized	-4.9	-1.6
SAMSO Update		
Standard	-4.3	-2.2
Normalized	-4.4	-1.9
Absolute mean	7.0	3.3
Actual cost	29.3	5.6

X. CONCLUSIONS

Can we say on the basis of the foregoing comparisons that certain estimating procedures or models appear preferable for some or all spacecraft? Before giving even a tentative answer to that question we wish to reiterate that no unique set of actual costs and technical characteristics is known to all model-builders and to Rand. We know that in some cases our figures differ from those used by others, and although we have gone to some pains to verify ours, we do not claim they are infallible. Hence, any comparison of model outputs contains more than the usual element of uncertainty, and the evaluation below should be regarded in that light.

Table 16 lists models that meet two conditions: First, the deviations do not exceed 25 percent or $200,000, whichever is greater. Second, the model must be listed at least three times in a row, thus indicating an applicability to a range of spacecraft types. The results are arrayed in that way to show which models have the broadest applicability relative both to types of spacecraft and to particular subsystems. With regard to nonrecurring costs, the array suggests that none of the models considered has general applicability for any subsystem except structure, and that applicability does not extend to low-cost spacecraft. Three SAMSO models appear to have some utility for estimating total nonrecurring cost, but again the low-cost spacecraft are excluded.

The picture is somewhat brighter for recurring costs. Four SAMSO models appear to be broadly useful for estimating structure costs; only MMS is not covered by at least one model. For communication subsystems no model meets the criteria above, but SAMSO Third Edition models qualify for attitude control. NASA HQ and SAMSO Update cover the test sample for electrical power subsystems, but with very little overlap. It should be said, however, that all models, using different variables and different functional forms, generate reasonably good estimates for electrical power subsystems.

Table 16

MODELS OF WIDEST APPLICABILITY

Type of Model	AEM	ATS-F	DSCS II	DSP II	MMS	S-3
		Nonrecurring Cost				
Structure		S3N	S3N	S3N	---	
		SUSt	SUSt	SUSt	---	
		SUN	SUN	SUN	---	
Total cost		S3St	S3St	S3St	---	
		SUSt	SUSt	SUSt	---	
		SUN	SUN	SUN	---	
		Recurring Cost				
Structure	S3St	S3St		S3St		S3St
	S3N	S3N				S3N
	SUSt	SUSt	SUSt			SUSt
	SUN	SUN				SUN
Attitude control	S3St		S3St	S3St		
	S3N		S3N	S3N		S3N
Electrical power		NASA HQ		NASA HQ		NASA HQ
	SUSt				SUSt	SUSt
	SUN				SUN	SUN
Total cost	S3St	S3St		S3St		
	S3N	S3N		S3N		S3N
	SUSt	SUSt		SUSt		
	SUN	SUN		SUN		
	SUP		SUP	SUP		

NOTE: S = SAMSO; 3 = Third Edition; U = 1977 Update; St = Standard; N = Normalized; P = Platform

Only SAMSO models estimate total cost within the limits established. Note, however, that none of the SAMSO models supplies an MMS estimate that is within 25 percent of the predicted cost of that spacecraft. We cannot be sure at this time whether the problem lies with the predicted cost, the models, or both.

The major problem to emerge from this review is the inability to estimate nonrecurring costs accurately, particularly for low-cost spacecraft. Since an unwarranted high estimate can be fatal to a

program early in the planning cycle, cost models should contain some sort of provisions to deal with low-cost spacecraft. Subjective adjustment factors based on use of flight-proven subsystems and components would be one way. Perhaps special-purpose cost models could be developed, but we are *not* attempting to cover the modeling problem here. The point is simply that weight is expected to be less of a constraint in the space-shuttle era, and spacecraft cost per pound should decline. Current spacecraft cost models do not cope with that possibility.

Another deficiency in the models examined is that they tend to be too inflexible or too subjective, particularly in the estimation of nonrecurring costs. Most models implicitly assume a fixed number of qualification units or prototypes and a fixed level of testing, rather than allow the analyst to input values appropriate to the program. At the other extreme we have the concept of an inheritance adjustment that seems too subjective unless the analyst has detailed information about the hardware required and the development program.

Technical characteristics predict recurring costs fairly well, but estimates of first-unit cost are generally better than estimates of quantity buys (a buy of four is considered a quantity buy in this context). Use of a conventional cost-quantity relationship to estimate spacecraft procurement is not always warranted because at very low production rates no cost reduction may occur. When a buy of four or more spacecraft is contemplated, it would be desirable to have a model that takes schedule into account as well as quantity.

Many of the models rely on inheritance adjustments or normalization techniques, and in principle such procedures should improve the quality of the estimates. We see two problems associated with them, however. The first is that they often require more detailed knowledge of a system than is available at the time parametric estimates are most useful. Guidelines and definitions that are meaningful at that time are essential. The second is that they are single-sided, that is, cost estimates can be increased but not decreased. Adjustment factors in the SAMSO model, for example, range from 1.0 to 2.55 for nonrecurring cost. There is no provision for a system of lower technology, and the result is that low-cost satellites are consistently overestimated. Either some provision

should be made to adjust cost downward as well as upward, or CERs should estimate absolute rock-bottom costs that could be adjusted only upward.

Estimates based on labor-hours rather than dollars work fairly well in the SAI model, eliminate the need for price-level adjustments, and allow the use of current, company-specific wage rates. If the consistent ratio of labor cost to total cost found by SAI can be confirmed, estimating in terms of labor-hours would simplify estimating techniques and give improved visibility into the components of cost. It would seem essential, however, to distinguish between engineering and production hours to establish an appropriate wage rate.

While working on the present study, we were struck by the effort expended by many researchers in a variety of organizations to seek out the same data. Judging from our own experience at Rand, about 80 percent of the time available for a project is consumed in collecting program, technical, and cost data, particularly the last. It would be highly advantageous if a single agency collected, processed, and stored spacecraft data and made them available to other organizations with a legitimate need-to-know. Agreement between USAF and NASA on the data required, standard subsystem descriptions, relationship to other spacecraft programs, etc., and an agreement to share such information would have at least two beneficial effects. First, the time and effort now required to collect data could be greatly reduced. Second, with more complete and comprehensive data, spacecraft cost models could be improved.

A final thought is that much of the work surveyed in this report appears to have been done in isolation, i.e., with little knowledge of modeling work performed previously by other organizations. It appears to us that everyone involved in this kind of work could benefit by greater knowledge of other studies in the field. Only by exchange of ideas will better, more reliable spacecraft cost models be developed; by initiating formal or informal procedures for such an exchange, the Air Force could advance the state of the art considerably.

BIBLIOGRAPHY

Brussell, E. R., et al., *Development of Cost Estimating Relationships for FLEETSATCOM,* PRC System Sciences Company, R-1800, Los Angeles, Calif., January 14, 1974.

Campbell, H. G., *Aerospace Price Indexes,* The Rand Corporation, R-568-PR, December 1970.

Clemens, D. B., et al., *Cost Estimating Relationships for GSFC Unmanned Satellites,* Goddard Space Flight Center, X-213-73-66, Greenbelt, Maryland, February 1973.

Dodson, E. N., et al., *Advanced Cost Estimating and Synthesis Techniques for Avionics,* General Research Corporation, CR-2-461, Santa Barbara, Calif., September 1975.

Dunkin, J. H., et al., *Cost Estimation for Unmanned Lunar and Planetary Programs,* Illinois Institute of Technology Research Institute, Technical Memorandum No. C-10, Chicago, Ill., January 1973.

Finnegan, W. P., et al., *Spacecraft Cost Estimation,* Illinois Institute of Technology Research Institute, Report No. C-6, Chicago, Ill., May 1966.

Fong, F. K., et al., *SAMSO Unmanned Spacecraft Cost Model--Updated Cost Estimating Relationships and Normalization Factors (An Interim Report),* USAF Space and Missile Systems Organization, Cost Analysis Division, El Segundo, Calif., January 1977.

Gompf, G. E., *Generalized Space Program Cost Model,* PRC System Sciences Company, PRC R-1451, Los Angeles, Calif., June 17, 1971.

Gruhl, W., *Spacecraft Platform Subsystem Complexity Level Cost Estimating Model,* Version III, National Aeronautics and Space Administration, Washington, D.C., November 1972.

Hadfield, B. M., *Satellite Systems Planning Costs,* The MITRE Corporation, MTP-138, Bedford, Mass., October 1972.

Kitchen, L. D., *Manpower/Cost Estimation Model--Automated Planetary Projects,* Science Applications, Inc., Report SAI 1-120-194-C1, Rolling Meadows, Ill., March 1975.

Levine, S. E., *Simplistic Spacecraft and Booster Cost Models,* The Aerospace Corporation, Satellite Systems Division, V, TOR-0077 (2404-30)-3, El Segundo, Calif., February 11, 1977.

Rowher, C. J., et al., *Space and Missile Systems Organization Unmanned Spacecraft Cost Model,* Third Edition, USAF Space and Missile Systems Organization, Cost Analysis Division, El Segundo, Calif., August 1975.